Journal of the Iowa Academy of Science: JIAS

Volume 101 | Number Article 8

1994

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Kara J. Potratz
Iowa State University

Mark L. Gleason
Iowa State Universtiy, mgleason@iastate.edu

Melanie L. Hockmuth
Iowa State University

Sharon K. Parker
Iowa State University

Glenn A. Pearston
Iowa State University

Recommended Citation

Potratz, Kara J.; Gleason, Mark L.; Hockmuth, Melanie L.; Parker, Sharon K.; and Pearston, Glenn A. (1994) "Testing the Accuracy and Precision of Wetness Sensors in a Tomato Field and on Turfgrass," *Journal of the Iowa Academy of Science: JIAS, 101(2),* 56-60.
Available at: https://scholarworks.uni.edu/jias/vol101/iss2/8

Jour. Iowa Acad. Sci. 101(2):56-60, 1994

Testing the Accuracy and Precision of Wetness Sensors in a Tomato Field and on Turfgrass

KARA J. POTRATZ, MARK L. GLEASON, MELANIE L. HOCKMUTH,
SHARON K. PARKER, and GLENN A. PEARSTON

Departments of Plant Pathology and Horticulture,
Iowa State University, Ames, IA 50011

Measurements of dew-period duration by painted, flat-plate, electronic wetness sensors at the top of the plant canopy in a tomato field and on adjacent turfgrass were compared with visual observations. The response range of sensors during the onset of dew sometimes exceeded 5 hr. but was less than 1 hr. on other nights. Sensors in the tomato field indicated dew formation occurred as much as 2 hr. earlier or later than dew became visible on adjacent tomato leaflets at the top of the crop canopy. A calibration threshold for sensors derived from a drying curve resulted in the underestimation of dew-period duration by up to 3.8 hr. and was less accurate than an empirically chosen threshold. Dew duration measured by sensors at the top of the tomato canopy and on adjacent turfgrass deviated from visual observation of dew duration at the top of the tomato canopy by about the same amount of time (0.8-hr. difference). These findings emphasize the need to use properly calibrated sensors for dew-period measurements and to calibrate dew-period measurements in a crop canopy.

KEYWORDS: biometeorology; epidemiology; leaf wetness

Many fungal pathogens of crop plants infect their hosts only after free water has been present on plant surfaces for a sufficient period of time. Numerous disease-warning models, which are used increasingly by researchers, crop consultants, and farmers to predict the risk of disease outbreaks, rely on measurements of wetness-period duration (Huber and Gillespie, 1992). Electronic sensors that detect wetness as a change in conductance (Huband and Butler, 1984) have largely replaced mechanical devices because the electrionic sensors are relatively inexpensive and easy to use (Huband and Butler, 1984). But there is no consensus on the optimal sensor type, design, or location in the environment (Huber and Gillespie, 1992; Huband and Butler, 1984; Sutton et al., 1984). Flat-plate, printed-circuit sensors (Davis and Hughes, 1970) are widely available commercially and are deployed extensively in the midwest U.S. in regional disease-warning systems, such as TOM-CAST on tomatoes (Gleason et al., 1992).

Disease-warning models based on wetness duration are only as reliable as the data input to them, but critical tests of the validity of wetness-duration measurements by electronic sensors are few. Several reports comparing performance of different wetness-sensor sizes and shapes (Huband and Butler, 1984; Gillespie and Duan, 1987; Butt and McGlinn, 1989), surface coatings (Gillespie and Kidd, 1978; Huband and Butler, 1984), and orientation (Gillespie and Kidd, 1978) found variability of up to several hours in wetness-duration measurements. It is also possible that individual sensors of the same design could vary in accuracy and precision because of either inherent differences among sensors or poor calibration (Sutton et al, 1984), but no tests assessing this possibility have been published.

The nature of a wetting event and sensor placement relative to a crop canopy can also influence wetness-duration data. Dew is the primary contributor to vegetative wetness duration (Davis and Hughes, 1970) and the variability of dew-duration measurements often exceeds that of rain periods (Huband and Butler, 1984); therefore, dew events are a logical focus for studies evaluating variability in wetness-sensor performance. Because wetness sensors used in disease-warning systems are often placed on turfgrass outside a crop field rather than within the field itself, it is important to assess the difference in wet-period duration between these two microenvironments.

The primary purpose of our study was to evaluate the accuracy and variability of electronic, flat-plate, printed-circuit wetness sensors during dew periods in a tomato field and on adjacent turfgrass.

MATERIALS AND METHODS

Wetness sensors.

The flat-plate, printed-circuit wetness sensors (Model 237, Campbell Scientific, Logan, UT) used in all trials were painted with flat latex paint by a proprietary process (R. Olson, Savannah, GA, pers. comm.) in order to enhance sensitivity to small water droplets, then heat-cured overnight in an oven to remove most of the water from the paint.

Field setup.

Processing-tomato seedlings (cv. Heinz 6004) were planted in a 15- x 15-m plot on a level, unobstructed site at the Iowa State University Horticulture Research Farm near Gilbert, IA, on 26 May 1993. Plant spacing was 1.5 m between rows and 0.3 m within rows. The planting was weeded regularly, fertilized according to standard horticultural recommendations, and sprayed with a fungicide (Bravo 720) weekly after June 21 to control foliar diseases. On 7 June, six wetness sensors (numbered 1-6) were placed side by side, 0.5 m apart, 30 cm above the ground, and faced north at a 45° angle above horizontal, at the center of the tomato plot midway between two rows of plants. Sensor faces were angled in order to prevent water from ponding on them. The sensor surfaces were at least 5 cm above the tomato canopy throughout the experiment. Six sensors of the same type

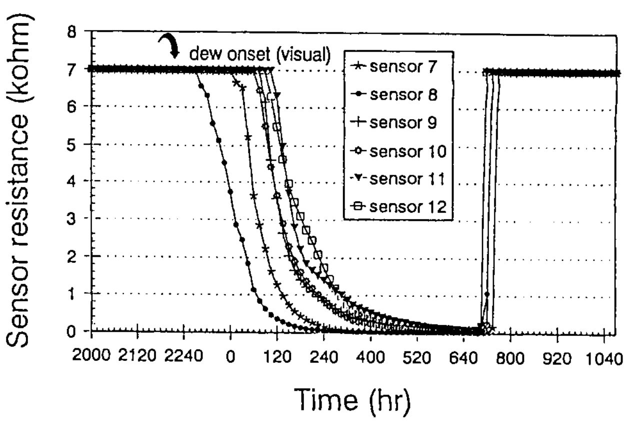

Fig. 1. Response (kohm) of six wetness sensors (sensors 7-12) located in turfgrass during a dew event on 25-26 July 1993.

Journal Paper No. J-15744 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa. Project No. 0159.

Table 1. **Differences between response times of six wetness sensors and visually observed times of onset and dryoff of dew in a tomato field.**

	Deviation from Visual Observation[a]											
Sensor	onset				dryoff				duration			
	high[b]	low[c]	mean[d]	S.D.[e]	high	low	mean	S.D.	high	low	mean	S.D.
1	−2.2[f]	−0.3	−1.1	0.8	+1.5	0.0	+0.1	0.8	+2.4[g]	+0.2	+1.2	0.9
2	+1.7	+0.2	+0.4	0.9	+1.0	0.0	+0.1	0.5	−1.6	+0.3	−0.4	0.8
3	+2.0	−0.3	+0.5	1.0	+1.2	+0.2	−0.1	0.7	−1.8	0.0	−0.6	0.8
4	+1.8	+0.3	+0.6	0.9	−1.3	0.0	−0.3	0.6	−2.0	−0.2	−0.9	0.7
5	−1.5	0.0	+0.2	0.9	±0.8	0.0	−0.2	0.6	−1.1	+0.3	−0.3	0.7
6	+1.7	+0.3	+0.5	0.9	+1.2	+0.2	0.0	0.7	−1.5	0.0	−0.5	0.7
mean	+0.6	+0.0	+0.2	0.9	+0.5	−0.1	−0.1	0.7	−0.9	+0.1	−0.3	0.8

[a] Difference between time of visually observed onset or dryoff on leaves in upper canopy and start (onset) and end (dryoff) of sensor response. Duration is the difference between visually observed and sensor-measured dew periods.

[b] Largest deviation of measured time from observed time (six dew events).

[c] Smallest deviation of measured time from observed time (six dew events).

[d] Average deviation of measured time from observed time (six dew events).

[e] Standard deviation (n=6)

[f] + = sensor response later than visual observation.
− = sensor response earlier than visual observation.

[g] + =duration of sensor measured dew period larger than observed dew period.
− = duration of sensor measured dew period smaller than observed dew period.

(numbered 7-12) were deployed approximately 15 m away on mowed turfgrass at the same height and orientation. Rainfall amount was recorded by a tipping-bucket rain gauge (Texas Electronics, Ft. Worth, TX) located on turfgrass adjacent to the tomato field. Sensors were checked periodically for cleanliness and correct orientation.

Every 10 min., The CR-10 datalogger calculated mean resistance (kohms) of wetness sensors from 5-min. readings of sensor voltage and excitation voltage (Campbell Scientific Inc., Logan, UT) and total rainfall amount (mm). Data were retrieved from the CR-10 by downloading to a personal computer at Iowa State University via a telephone line.

Visual observation of dew.

The timing of the start and end of dew periods was noted visually on six predominantly clear-sky nights in July and August. Each night, the formation of dew on tomato leaves at six observation sites adjacent to the wetness sensors was assessed every 20 min. beginning at sunset until dew formed. A flashlight and hand lens were used to help see small dew droplets. A dew period was arbitrarily assumed to have begun when dew was visible on the uppermost leaflets at three or more of the observation sites. These leaflets were used for observations because they were closest to the position of the electronic sensors. Readings resumed at sunrise and continued until dryoff, which was arbitrarily assumed to be the time when the uppermost leaflets at half or more of the observation sites were completely dry. The visually observed times of dew onset and dryoff were taken to be the true times of these events for determining the accuracy of the sensor measurements of dew timing.

RESULTS

Reponse of painted, flat-plate sensors to wetness.

Wetness sensors indicated a value of 6999 kohm when dry (Fig. 1). Sensor response to wetness was assumed to begin when kohm readings were below this value and to end when readings increased to this value. In general, sensor response to dew onset was more gradual and variable than response to dew dryoff.

Deviation of sensor response from visual observation.

Painted, flat-plate sensors located in a tomato field during six dew events underestimated observed dew duration by an average of 0.3 hr. (Table 1). There was considerable variability among sensors in measuring the timing of dew onset. During onset of individual dew events, some sensors responded up to 2 hr. earlier whereas others responded up to 2 hr. late. Individual sensors averaged as much as 1 hr. early or as much as 40 min. late compared with visual determination of onset time. On the average, the sensors responded late to dew onset and early to dew dryoff (Table 1).

Range of sensor variation.

The range of the timing of sensor response was much larger for dew onset than for dew dryoff (Fig. 1 and Table 2). On a given night, the detection of onset among sensors varied by up to 5.5 hr., but as little as 0.3 hr. for detection of dryoff.

Dryoff calibration.

When a value of 900 kohm, derived in June 1993 from laboratory measurements of dryoff of the same twelve wetness sensors used in field trials (Gleason, unpublished data), was used as a threshold between wet and dry, dew duration was underestimated by average 1.5 hr. (Table 3) compared with only 0.3 hr. for a threshold of 6999 kohm (Table 1). Deviation from observed dew periods for the 6999-kohm threshold was much greater for dew onset than for dew dryoff, and both the 900-and 6999-kohm thresholds resulted in late response to onset and a slightly early response to dryoff.

Sensor response to onset of dew vs. rain.

All sensors responded rapidly and synchronously to the onset of rain (Fig. 2A), but response to dew onset was more variable. The start of sensor response was spread out over 0.5 hr. during rapid onset of dew (Fig. 2B), over 1 hr. during more gradual onset of dew (Fig. 2C), and over 4 hr. by even more gradual dew onset (Fig. 2D).

Turf vs. field.

The response of coated, flat-plate sensors to dew onset began an average of 0.8 hr. later on turfgrass than at the top of the vegetation canopy in the adjacent tomato field (Table 4). On average, dew dryoff

Table 2. Time from sunset to dew onset and range of sensor readings for dew onset, dryoff, and duration during six dew events.[a]

Date	time from sunset to dew onset (hr)[b]	Range of Sensor Variation (hr) onset	dryoff	duration
7/19-20/93	1.6	0.5	0.3	0.7
7/25-26/93	2.2	2.2	0.3	2.3
7/28-29/93	3.3	5.3	0.3	5.5
7/29-30/93	0.3	3.5	0.8	3.0
8/10-11/93	0.5	1.0	0.5	1.8
8/12-13/93	0.2	1.3	0.8	1.1
mean		2.3	0.5	2.4

[a] Data was taken from six painted, flat plate sensors located on mowed turfgrass.

[b] Time of dew onset was determined by visual observations of tomato leaflets at the top of the crop canopy in a processing-tomato field adjacent to the turfgrass site.

was sensed at nearly the same time in both locations, and measured times of dryoff were in close agreement with visual observations.

DISCUSSION

This is the first published study comparing the behavior of electronic wetness sensors of the same type under field conditions. Earlier studies have compared behavior among different types of wetness sensors (Sutton et al, 1984; Huband and Butler, 1984) or commercial wetness-monitoring equipment (Butt and McGlinn, 1989). The fact that the range of sensor response averaged 2.4 hr. per dew period suggests that using one of these sensors per field site — a common practice in Integrated Pest Management networks (Gleason et al., 1992) — could result in large errors in estimating wetness duration and in implementing disease-warning systems. For the TOM-CAST disease-warning system on processing tomatoes (Gillespie et al., 1993), for example, a 2.4 hr. variation in dew duration could result in a difference of one Disease Severity Value per dew event. Assuming five dew events per wk. during 1 July through 15 September and a fungicide-spray threshold of 18 summed Disease Severity Values, sensor-to-sensor variation could result in a difference of three fungicide sprays per season (Gleason, unpublished data). One solution to the sensor-variability problem is to calibrate the sensors before use. Our data show that variability in sensor response during dew onset is greater than during dew dryoff, and that the rate of dew onset varies considerably among dew events. Butt and McGlinn (1989) noted that sensor response was far more variable in still air (such as during dew onset) than when wind was present. As in our study, Huband and Butler (1984) noted that sensor variability was greatest when dew onset was slow, less when dew onset was rapid, and minimal for the start of rain events. To calibrate a sensor reliably, therefore, it may be necessary to determine its behavior during the onset of several dew events on a crop of interest, then apply an appropriate time-correction factor or adjust the resistance value used as the wet-dry threshold. By using a wetness threshold derived from events other than dew onset, such as dryoff under laboratory conditions (Gleason, unpublished data), variability among sensors is likely to be underestimated and can result in the underestimation of dew-period duration. An alternative to field calibration would be positioning several sensors at

Table 3. Observed times of onset and dryoff of dew in a tomato field in comparison to times from painted, flat-plate sensors when 900 mv was used as a wetness threshold for the sensors.

	Deviation from Visual Observation											
Sensor	onset				dryoff				duration			
	high[b]	low[c]	mean[d]	S.D.[e]	high	low	mean	S.D.	high	low	mean	S.D.
1	−2.0[e]	−0.2	−0.6	0.8	+1.5	−0.2	0.0	0.8	+2.2[f]	0.0	0.7	1.1
2	+3.2	−0.3	+1.6	1.1	+1.0	0.0	0.1	0.5	−3.1	0.0	−1.6	1.1
3	+4.0	0.0	2.1	1.3	−1.2	+0.2	−0.2	0.8	−3.8	−1.0	−2.2	1.0
4	+3.5	0.0	+1.9	1.1	−1.3	0.0	−0.3	0.6	−3.7	−1.3	−2.4	1.1
5	+2.7	−1.2	+1.3	1.3	+0.8	0.0	−0.2	0.6	−3.0	+0.3	−1.5	1.2
6	+3.7	0.0	+2.0	1.2	+1.2	0.0	−0.0	0.8	−3.3	−0.9	−2.0	0.9
mean	+2.5	−0.3	+1.4	1.1	+0.3	0.0	−0.1	0.7	−2.5	−0.5	−1.5	1.1

[a] Largest deviation of measured time from observed time (six dew events).

[b] Smallest deviation of measured time from observed time (six dew events).

[c] Average deviation of measured time from observed time (six dew events).

[d] Standard deviation (n=6)

[e] + =sensor response later than visual observation.
—=sensor response earlier than visual observation.

[f] + =duration of sensor measured dew period than observed dew period.
—=duration of sensor measured dew period smaller than observed dew period.

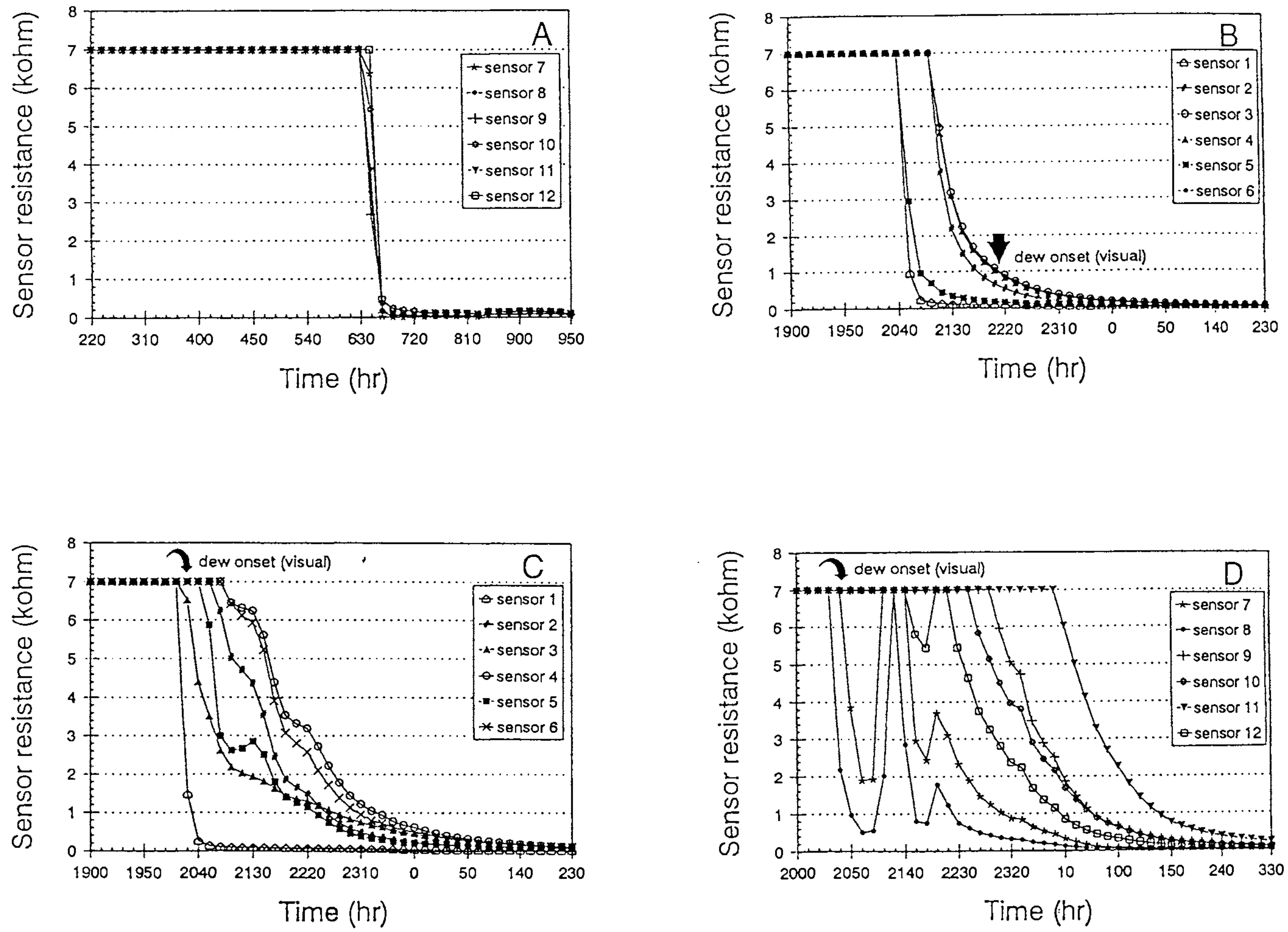

Fig. 2. Response (kohm) of wetness sensors located in turfgrass (sensors 7-12) during a rain event on 13 July (A) and during onset of dew in an adjacent tomato field on 19-20 July (B), in the tomato firle don 29-30 July (C), and on turfgrass on the same night (29-30 July) (D).

Table 4. Timing of dew onset, dryoff, and duration measured by flat-plate wetness sensors located above a tomato canopy and on adjacent turfgrass compared to visual observations of dew timing on upper leaves of tomatoes.

	Deviation from Visual Observation[a]											
	Turf						Field					
Date	onset	S.D.[b]	dryoff	S.D.	duration	S.D.	onset	S.D.	dryoff	S.D.	duration	S.D.
7/19-20/93	+1.0[c]	0.2	−0.5	0.2	−1.6[d]	0.3	−1.2	0.3	−0.8	0.4	+0.3	0.5
7/25-26/93	+1.8	0.8	−1.1	0.2	−2.9	0.9	+0.2	0.9	−0.4	0.1	−0.6	1.1
7/28-29/93	+0.7	2.2	−0.2	0.1	−0.9	2.2	+1.0	1.6	+0.1	0.2	−0.9	1.7
7/29-30/93	+1.4	1.4	−0.2	0.3	−1.6	1.2	0.0	0.3	−0.3	0.2	−0.4	0.4
8/10-11/93	+0.4	0.6	+0.2	0.2	−0.1	0.6	+0.5	0.5	0.0	0.2	−0.5	0.4
8/12-13/93	+0.4	0.5	+1.1	0.3	+0.8	0.4	+0.5	0.4	+1.0	0.4	+0.5	07
Mean	+1.0	1.0	−0.1	0.2	−1.1	0.9	+0.2	0.7	−0.1	0.3	−0.3	0.8

[a] Mean deviation of six painted, flat-plate sensors from visual observation for dew onset, dryoff, and duration.
[b] Standard deviation (n=6)
+ = sensor response later than visual observation.
− = sensor response earlier than visual observation.
[c] + =duration of sensor measured dew period longer than observed dew period.
[d] − = duration of sensor measured dew period shorter than observed dew period.

each field site. This strategy has been recommended to account for spatial variability in wetness duration within a crop canopy (Huber and Gillespie, 1992), but it may also be used to compensate for variability among sensors.

The relatively small (0.8-hr.) difference in average dew-period duration measurements between the top of a processing-tomato canopy and adjacent turfgrass supports the idea that turfgrass sites may be useful as permanent stations for approximating wetness duration in neighboring crops such as tomatoes. Permanent weather-monitoring sites offer advantages over in-field monitoring in that they are undisturbed by agronomic activities and are often more accessible. However, the timing of dew onset and dryoff on leaves with a tomato canopy is likely to differ significantly from that at the top of the canopy due to microenvironmental gradients of wind, humidity, and exposure to the sky. Estimates of crop-canopy wetness duration derived from measurements on turfgrass should therefore be calibrated against wetness measurements inside the crop canopy.

ACKNOWLEDGEMENTS

The study was supported by an internship grant to the senior author by the Program for Women in Science and Engineering at Iowa State University. We thank S.E. Taylor for advice on experimental design and X.B. Yang and F.W. Nutter, Jr., for helpful suggestions during preparation of the manuscript.

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