Special Report

Effects of Coating, Deployment Angle, and Compass Orientation on Performance of Electronic Wetness Sensors During Dew Periods

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ABSTRACT

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Response of electronic, printed-circuit wetness sensors was compared to visual observations of free water on processing-tomato leaflets during 13 dew-onset and 11 dew-dryoff events. Deployment angle and painting of the sensor surface significantly ($P < 0.01$) influenced the mean absolute time difference between observation of the first wet or dry leaflet at the top of the tomato canopy and the start of sensor response (kΩ) to dew onset or dryoff, respectively. Compass orientation of painted sensors deployed at 45° to horizontal had no significant effect on response to dew onset or dryoff. For sensors deployed at 45° during dew onset, mean absolute time difference between the first observed wet leaflet and the start of unpainted sensor response was 4.00 h, compared to 0.58 and 1.09 h for sensors with three and nine coats of paint, respectively. At deployment angles of 30 or 0°, paint coating had a lesser influence on time differences between visual observation and sensor response to dew onset. During dew dryoff, absolute time differences between visual confirmation of the first dry leaflet and the start of sensor response were ≤1.03 h for all sensors. Trends were similar when the visual observation criterion was 50% wet or dry leaflets during dew onset or dryoff, respectively, rather than first wet or dry leaflet. Standard deviation of sensor response during dew onset was generally larger for unpainted sensors than for sensors with three coats of paint, especially when deployed at a 45° angle. The apparent temperature of unpainted sensors at 0 or 30° deployment angles decreased much more rapidly during the period preceding dew onset than for painted sensors at the same deployment angles, whose apparent temperatures cooled at rates similar to those of tomato leaflets positioned at these angles. The results indicate that deployment angle can significantly affect accuracy and precision of dew-duration measurements by unpainted, but not painted, electronic wetness sensors.

Additional keywords: leaf wetness, wetness duration

The presence of free water on leaves triggers activity by many foliar pathogens of crop plants. The duration of periods of leaf wetness is therefore widely used as a critical determinant of risk that a crop disease epidemic will occur. Disease-warning systems, which are designed to improve the efficiency of disease-management practices such as fungicide spraying, often employ leaf wetness duration as an input parameter (2,7,11).

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Flat, printed-circuit wetness sensors (3,5) are widely used by researchers, consultants, and growers to measure wetness duration because they are commercially available, inexpensive, durable, and easy to use (6). These devices, positioned in or near a crop canopy, sense changes in electrical resistance resulting from wetting or drying of the sensor surface. Resistance, recorded at timed intervals, is converted to wetness duration using a resistance threshold determined by calibration trials (9).

Despite the key role of electronic wetness sensors in implementing disease-warning systems, few guidelines for their deployment are available and even fewer evaluations of their accuracy and precision have been reported. Although accuracy and precision can be affected markedly by sensor size and shape (4,6), orientation (5), presence and color of paint coating (5), and even variability among apparently similar sensors (9), the magnitude of these influences has not been quantified in replicated trials.

Wetness sensor responses are often more variable during dew than rain periods (6,9). Dew also contributes the majority of wetness hours during growing seasons in many parts of the world (3); therefore, it makes sense to test wetness sensor performance during dew periods (9). The purpose of our study was to quantify effects of sensor coating and position on sensor response to the onset and dryoff of dew in a crop canopy.

MATERIALS AND METHODS

Wetness sensors. Flat, printed-circuit wetness sensors (Model 237, Campbell Scientific, Logan, UT) were spray-painted with an undercoat of flat black latex paint (3), followed by either two or eight coats of flat, white latex paint (a total of three or nine coats of paint). The purpose of painting the sensors was to increase their sensitivity to small water droplets (3,5). The white paint, whose composition was proprietary, was developed to mimic the emissivity of plant leaves (R. Olson, Savannah, GA, *personal communication*). Sensors were oven-dried for 24 h between each coat of paint to remove most of the moisture from the paint. Unpainted sensors served as controls. Each wetness sensor was mounted on a section of PVC tubing (5 cm in diameter) which was clamped to a metal stake for deployment in the field.

Design of field experiment. Processing-tomato seedlings (cv. Heinz 1916) were transplanted on 27 May 1997 to a level, unobstructed site at the Iowa State University Horticulture Research Farm near Gilbert, Iowa. The plot included 11 rows, 15.2 m long and spaced 1.5 m apart, with 0.3 m between plants in each row. The plot was weeded manually and sprayed with chlorothalonil (Bravo 720, 3.0 pt/A) and copper hydroxide (Champ F, 1.5 pt/A) every 7 to 10 days to control fungal and bacterial diseases, respectively.

On 7 July, wetness sensors were deployed parallel to the tomato rows and 5 cm above the maximum canopy height in order to approach the upper canopy as closely as possible without obstructing the sensors. Sensor height was adjusted periodically to maintain this separation. A total of 12 wetness sensors were placed 0.9 m apart in each of the two center rows of the plot. Sensors in each row included (i) a factorial combination of three coating treatments (unpainted, three coats, or nine coats of paint) × three deployment angles (0°, 30°, or 45° from horizontal) which were faced north and (ii) sensors with three coats of paint, angled at 45°, which were faced east, west, or south. Sensor placement was randomized within each row, and all sensors were ≥1.5 m from the end of a row. Deployment angles were verified periodically using an adjustable protractor with an attached spirit level. Other sensors included a relative humidity/temperature sensor (Vaisala Model HMP 35C, Campbell Scientific) at the top of the tomato canopy and an anemometer (Model 014A, Met One Instruments, Grants Pass, OR) at a 1.5-m height within the plot. All sensors were connected through a multiplexer (AM 416, Campbell Scientific) to a datalogger (CR10, Campbell Scientific) which recorded data every 5 min and output means every 10 min.

Visual observations of dew. A total of 12 unobstructed tomato leaflets at the top of the tomato canopy were tagged for visual observation of dew formation and dryoff. Leaflets were selected to represent a wide range of slope and aspect orientation. The tagged leaflets were replaced when they became folded, senescent, or overshadowed by other leaflets. Predominantly clear, still nights during July and August were chosen for dew observations. Observations began just prior to sunset, were repeated at 20- to 30-min intervals until dew onset, and resumed at sunrise until dryoff occurred. For dew-onset observations, a fluorescent lantern was used to visually detect changes in leaflet reflectance caused by the appearance of a thin film of dew. The number of leaflets with visible dew was recorded until ≥50% of the tagged leaflets became wet during dew onset, and until ≥50% of the leaflets became dry during dew dryoff.

Infrared measurements of apparent temperature. Two terminal leaflets at the top of the canopy were positioned facing north at an angle of 0, 30, or 45° from horizontal. The desired leaflet orientation was accomplished by fitting the leaflets between three thin rubber bands stretched across wire frames secured to wooden dowels. An infrared thermometer (Teletemp Inc., Model AG-42) was used to take readings of apparent temperature (temperature influenced by the emissivity of a measured object and radiation reflected from the surrounding environment, as well as the actual temperature of the object) from the surface of positioned leaflets, as well as of all north-facing wetness sensors in one row of tomatoes, on 15 August. Temperature readings began approximately 30 min before sunset, were repeated at

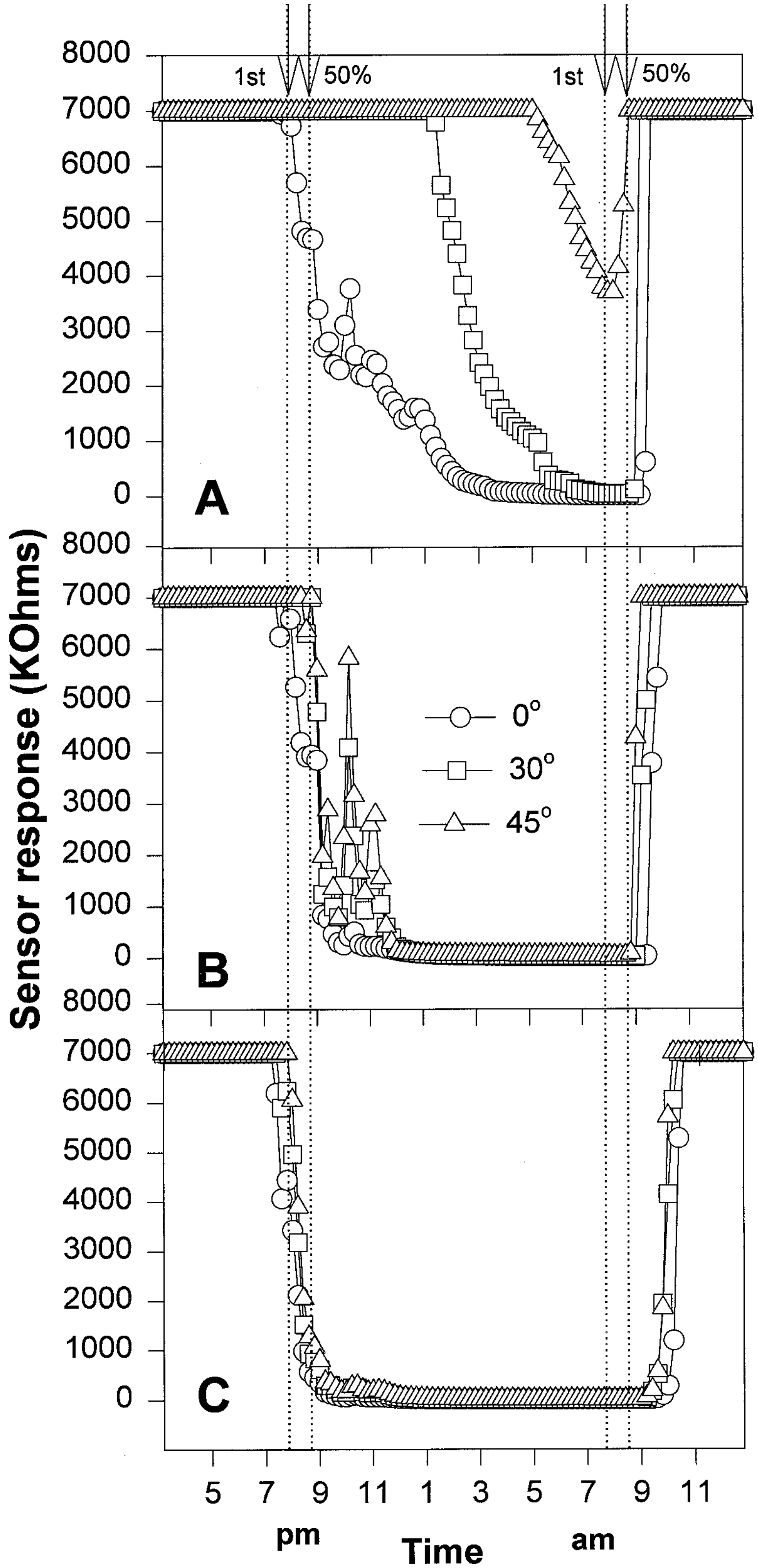

Fig. 1. Changes in resistance (kΩ) of electronic wetness sensors during a dew event in a processing-tomato canopy on 2 to 3 August. Sensors were deployed at 0°, 30°, or 45° angles to horizontal, and were **(A)** unpainted or had **(B)** three coats or **(C)** nine coats of paint. Time of visual observation of dew onset (evening) or dryoff (morning) on the first leaflet in the 12-leaflet observation set = "1st" and time of visual observation of dew onset or dryoff on ≥6 of the 12 leaflets in the observation set is designated by "≥50%". Data points are means of two replicate sensors. Sensors were facing north and positioned 5 cm above a processing-tomato canopy.

intervals of 10 to 20 min, and ended after dew onset was observed. For each reading, the thermometer was positioned 7 to 8 cm above and slightly to the south of the leaflet or sensor surface. Apparent temperature was recorded for each leaflet or sensor as soon as the thermometer reading stabilized (3 to 5 sec).

Data analysis. Mean electrical resistance (kΩ) of paired wetness sensors (same paint treatment, deployment angle, and compass orientation) was averaged for 13 dew-onset events and 11 dew-dryoff events. Sensor response was assumed to begin when electrical resistance began to decline in the evening (dew onset) or rise in the morning (dew dryoff). Analysis of variance (ANOVA) using a general linear model procedure (SAS Inc., Goldsboro, NC) was used to assess influence of sensor coating and deployment angle on the absolute time difference between the start of sensor response to dew onset and the time of visual observation of dew on (i) the first leaflet or (ii) ≥50% of monitored leaflets. A similar analysis was conducted for dew dryoff.

RESULTS

The timing of unpainted-sensor response to dew onset was strongly influenced by the angle of deployment. On the night of 2 to 3 August, for example, unpainted sensors deployed at 0° responded at nearly the same time as the first visual observation of dew on a tomato leaflet, whereas sensor response began progressively later for sensors deployed at 30 and 45° (Fig. 1). In contrast, sensors with three or nine coats of paint responded almost uniformly to dew onset regardless of deployment angle. Sensors responded to dew dryoff more synchronously than to dew onset, regardless of deployment angle or paint coating.

For 13 dew-onset events, mean absolute time difference between the start of sensor response and visual observation of the first wet leaflet was significantly ($P < 0.0001$) affected by sensor coating and deployment angle (Table 1). Although mean absolute time difference between the start of sensor response and visual observation of the first dry leaflet were also significant ($P < 0.0001$), the magnitude of these differences was considerably smaller than for dew onset (Table 2). The interaction of sensor coating with deployment angle was significant ($P < 0.0001$) for both dew onset and dryoff (Table 1). ANOVA results were similar when times for 50% wet leaflets (dew onset) and 50% dry leaflets (dew dryoff) were substituted for first wet or dry leaflet, respectively (*data not shown*).

Compass direction did not significantly affect the time differences between initiation of sensor response and visual observations of dew onset or dryoff (Table 1). After sunrise, however, east-facing sensors

Table 2. Absolute mean time (h) from visual observation of first wet leaflet (dew onset) or first dry leaflet (dew dryoff) in a 12-leaflet observation set at the top of the tomato canopy until start of sensor response for 13 dew onset and 11 dew dryoff events

	Sensor angle					
	0°		30°		45°	
Sensor treatment	Mean	SD	Mean	SD	Mean	SD
Dew onset[a]						
Unpainted	1.55	1.43	2.11[b]	1.88	4.00[c]	2.72
3 coats of paint	0.86	1.08	0.85[d]	1.20	0.58[e]	0.54
9 coats of paint	1.15	1.49	1.06	1.47	1.09	1.57
Dew dryoff[f]						
Unpainted	0.30	0.28	0.37	0.34	1.03[g]	0.90
3 coats of paint	0.35	0.21	0.29	0.32	0.60[g]	0.51
9 coats of paint	0.44	0.31	0.27	0.28	0.27	0.22

[a] n = 26 (13 events × two replicate sensors) unless otherwise noted.
[b] n = 23.
[c] n = 17.
[d] n = 25.
[e] n = 24.
[f] n = 22 (11 events × two replicate sensors) unless otherwise noted.
[g] n = 20.

Table 1. Analysis of variance of absolute value of time difference (h) between start of sensor response and visual observation of first wet leaflet (dew onset) or first dry leaflet (dew dryoff)[a]

Parameters	Replication	Sensor coating	Sensor angle	Coating × angle	Compass direction	Error
Sensor coating and angle experiment [b]						
Dew onset						
df	1	2	2	4	…	98
MS	0.12	49.92	6.11	13.35	…	0.55
F	0.23	90.08	11.04	24.10	…	…
P > F	0.6318	<0.0001	<0.0001	<0.0001	…	…
Dew dryoff						
df	1	2	2	4	…	87
MS	0.08	0.79	1.82	1.15	…	0.05
F	1.68	17.08	39.30	24.91	…	…
P > F	0.20	<0.0001	<0.0001	<0.0001	…	…
Sensor compass direction experiment [c]						
Dew onset						
df	1	…	…	…	3	44
MS	1.03	…	…	…	0.76	0.82
F	1.27	…	…	…	0.92	…
P > F	0.2667	…	…	…	0.4369	…
Dew dryoff						
df	1	…	…	…	3	38
MS	0.22	…	…	…	0.56	0.21
F	1.07	…	…	…	2.66	…
P > F	0.3085	…	…	…	0.0622	…

[a] Sensor response to dew onset was assumed to begin where kΩ values declined below datalogger reading of 6,999 kΩ. Sensor response to dew dryoff was assumed to begin when kΩ values began to increase after sunrise. A total of 12 preselected leaflets at the top of the tomato canopy were observed during dew onset and dryoff events. First wet leaflet = first leaflet of the observation set was visually observed to be wet. First dry leaflet = first leaflet of the observation set was observed to be completely dry.
[b] Factorial combination of three sensor coatings × three sensor angles in a randomized complete block design with two replications.
[c] Treatments were four compass directions (N, W, S, E) in a randomized complete block with two replications. All sensors had three coats of paint and were angled at 45° to horizontal.

began to indicate dryoff approximately 20 min, on average, before sensors deployed in other directions began to respond (*data not shown*).

The absolute time difference between visual appearance of dew on the first monitored leaflet and the start of response of unpainted sensors became much larger for unpainted sensors than for sensors with three coats of paint as deployment angle increased from 0 to 45° (Table 2). As the deployment angle of unpainted sensors increased, sensor response lagged behind the time of visually confirmed appearance of dew to an increasing extent (Fig. 1). For sensors deployed at 45°, the mean absolute time difference between the first observed wet leaflet and start of response was 4.00 h for unpainted sensors, compared to 0.58 h for sensors with three coats of paint. When the visual criterion for dew onset was ≥50% wet leaflets, absolute time differences for visual observations versus the start of sensor response increased for painted sensors but were still considerably smaller than for unpainted sensors, especially for sensors with three coats of paint (Table 3). Sensors with three coats of paint had smaller absolute-time differences than sensors with nine coats of paint during dew onset. Standard deviations were generally smaller for sensors with three coats of paint than for the other sensors during dew onset (Tables 2 and 3).

Unpainted sensors sometimes failed to respond at all during dew onset. Unpainted sensors deployed at 30 and 45°, for example, failed to respond to dew onset 15.4 and 30.8% of the time, respectively (M. L. Gleason, *unpublished data*). All painted sensors responded during each dew event.

During the evening of 15 August, the apparent temperature of wetness sensors with three coats of paint decreased at approximately the same rate as tomato leaflets at the top of the canopy, regardless of deployment angle, and similar to the cooling rate of the ambient air (Fig. 2A). Rates of decrease in the apparent temperature of unpainted sensors were much more sensitive to deployment angle than either painted sensors or tomato leaflets. The apparent temperature of the unpainted sensor at the 0° angle decreased to nearly 15°C below ambient air temperature by the time dew began to form (about 10:00 P.M.). The apparent temperature of the 45°-angle unpainted sensor cooled at about the same rate as the painted sensors and leaflets, while the 30°-angle unpainted sensor cooled at an intermediate rate. During the same evening, resistance of the painted sensors declined sharply during dew onset, except when a slight increase in wind between 9:00 and 10:00 P.M. (Fig. 2) appeared to have caused enough drying to raise resistance temporarily on the 30- and 45°-angle sensors (Fig. 2B). The unpainted sensor at the 0°-deployment angle responded to dew onset at about the same time as the painted sensors, but the unpainted sensors at 30 and 45° did not begin to respond until 1.5 and 2.5 h later, respectively (*data not shown*).

DISCUSSION

This study is the first to document interaction between sensor angle and coating in detecting the timing of dew events. During dew onset, painted wetness sensors were considerably less sensitive to the angle of deployment than unpainted sensors. Response of unpainted sensors generally lagged behind observed dew onset as the sensor angle to horizontal was increased, and these sensors sometimes failed to respond at all during dew events. Earlier studies reported that painting the surface of electronic wetness sensors enhanced sensitivity to dew onset but did not present replicated data in support of these observations (3–5). Latex paint reduces surface tension of the sensor and allows small amounts of water to spread uniformly across the sensor surface, thereby reducing sensor resistance sooner than on unpainted sensors during dew onset (3,5). In our study, sensors with three coats of paint detected the time of dew onset more accurately than sensors with nine coats of paint. These data support Davis and Hughes' (3) recommendation to apply three to five coats of paint to printed-circuit sensors.

Leaves cool by radiation. The extent of cooling is governed by dew point, wind, and sky conditions (clear sky generally means more rapid cooling). During dew onset, painted sensors respond much like leaves to radiation, wind, and dew point. In contrast, unpainted sensors behave more like mirrors; they have greatly reduced radiation response because of the low thermal emissivity of the sensor surface (12). The emissivity effect is greatest for inclined surfaces (10), resulting in delayed or absent response during dew onset (Figs. 1 and 2).

Mean time differences of 4 h in detecting dew-period duration by unpainted wetness sensors could seriously bias the operation of disease-warning systems that rely on wetness-duration data. For example, assuming that daily wetness duration data input to the TOM-CAST system for control of fungal diseases of tomatoes (8) were underestimated by 4 h/day over an 11-week monitoring period, that dew occurred on 5 days/week, that TOM-CAST's daily disease severity values (DSV) rating were underestimated by one DSV on approximately two-thirds of these days (37 days), and that the action threshold for fungicide spraying were set at a sum of 18 DSV (all reasonable assumptions for the Midwest United States), TOM-CAST would recommend two fewer fungicide sprays per season than if wetness-duration data were accurate (M. L. Gleason, *unpublished data*). Fewer fungicide sprays and delays in fungicide application resulting from wetness-duration underestimates could increase the risk of epidemics of TOM-CAST's target diseases: early blight (*Alternaria solani),* Septoria leaf spot (*Septoria lycopersici*), and anthracnose fruit rot (*Colletotrichum coccodes*). Similar errors could result when using other disease-warning systems dependent on wetness duration. The relatively large standard errors incurred by the unpainted sensors in estimating the time of dew onset would complicate attempts to apply a correction factor. If unpainted wetness sensors are used to monitor duration of dew periods, the angle of deployment should be measured and maintained carefully during calibration and field use. For painted sensors, on the other hand, deployment angle appears to be a much less critical determinant of accuracy and precision.

Although east-facing, painted sensors responded to dew dryoff about 20 min sooner than painted sensors facing in other directions, this time difference appears negligible in comparison to differences noted for unpainted sensors during dew onset. Reflection of solar radiation by the white paint on the sensors served to slow

Table 3. Mean time (h) from visual observation of ≥50% wet leaflets (dew onset) or ≥50% dry leaflets (dew dryoff) to start of sensor response for 13 dew onset and 11 dew dryoff events

	Sensor angle					
	0°		30°		45°	
Sensor treatment	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Dew onset[a]						
Unpainted	2.12	1.71	2.04[b]	1.60	3.80[b]	2.36
3 coats of paint	1.54	1.72	1.23[c]	1.49	1.19[c]	1.41
9 coats of paint	1.98	2.12	1.93	2.10	1.94	2.17
Dew dryoff[d]						
Unpainted	0.65	0.38	0.95	0.46	1.37[e]	0.88
3 coats of paint	0.56	0.32	0.80	0.50	1.16[f]	0.66
9 coats of paint	0.47	0.34	0.68	0.34	0.85	0.44

[a] n = 26 (13 events × two replicate sensors) unless otherwise noted.
[b] n = 17.
[c] n = 24.
[d] n = 22 (11 events × two replicate sensors) unless otherwise noted.
[e] n = 21.
[f] n = 20.

the drying rate of east-facing sensors after sunrise (T. Gillespie, University of Guelph, Guelph, Ontario, *personal communication*).

Our data for tomato leaflets also corroborate Davis and Hughes' (3) observation that, after sunset, apparent temperature of painted flat-plate sensors decreased at almost the same rate as nearby soybean leaves. For the single night of apparent temperature data recorded in our study, temperature readings of unpainted sensors angled at 30 and 0° declined much more rapidly than for tomato leaflets positioned at the same angles. At an angle of 0°, apparent temperature of unpainted sensors declined so rapidly that electrical resistance began to decrease at approximately the same time as dew began to form on the 12 tomato leaflets in the observation set. Although the unpainted sensors deployed at 0° detected the timing of dew onset and dryoff nearly as accurately as sensors with three coats of paint (Tables 2 and 3), other researchers have pointed out that horizontal orientation of flat sensors does not represent normal leaf orientation realistically (5) and may tend to increase variability in drying time among sensors (1).

Our findings illustrate that evaluation of the accuracy of wetness sensors is influenced by the criteria used as standards of comparison. For example, the magnitude of time differences between sensor response and visual observation of dew onset was affected noticeably by whether the visual-observation criterion was the first wet leaflet or ≥50% wet leaflets (Tables 2 and 3). Even for tomato leaflets at the top of the canopy, dew formation occurs asynchronously due to differences in such factors as leaflet orientation and wind exposure. Within the canopy, dew duration will be much more variable than on the uppermost leaves due to more pronounced microenvironmental gradients affecting dew formation and dryoff (7). Consequently, wetness sensors should be calibrated against wetness observations in portions of a crop canopy that are of greatest importance for the end users of the information.

As more disease-warning systems are implemented in cropping systems, the need to critically examine the accuracy of weather inputs to these systems is increasing. Automated weather instrumentation makes it easy to acquire vast quantities of weather data whose accuracy and precision have not been evaluated (11). To insure that disease-warning systems based on wetness duration are reliable to use, it is essential to evaluate the accuracy of the input data. Our study emphasizes the need to consider wetness sensor coating and deployment angle when measuring the duration of dew periods.

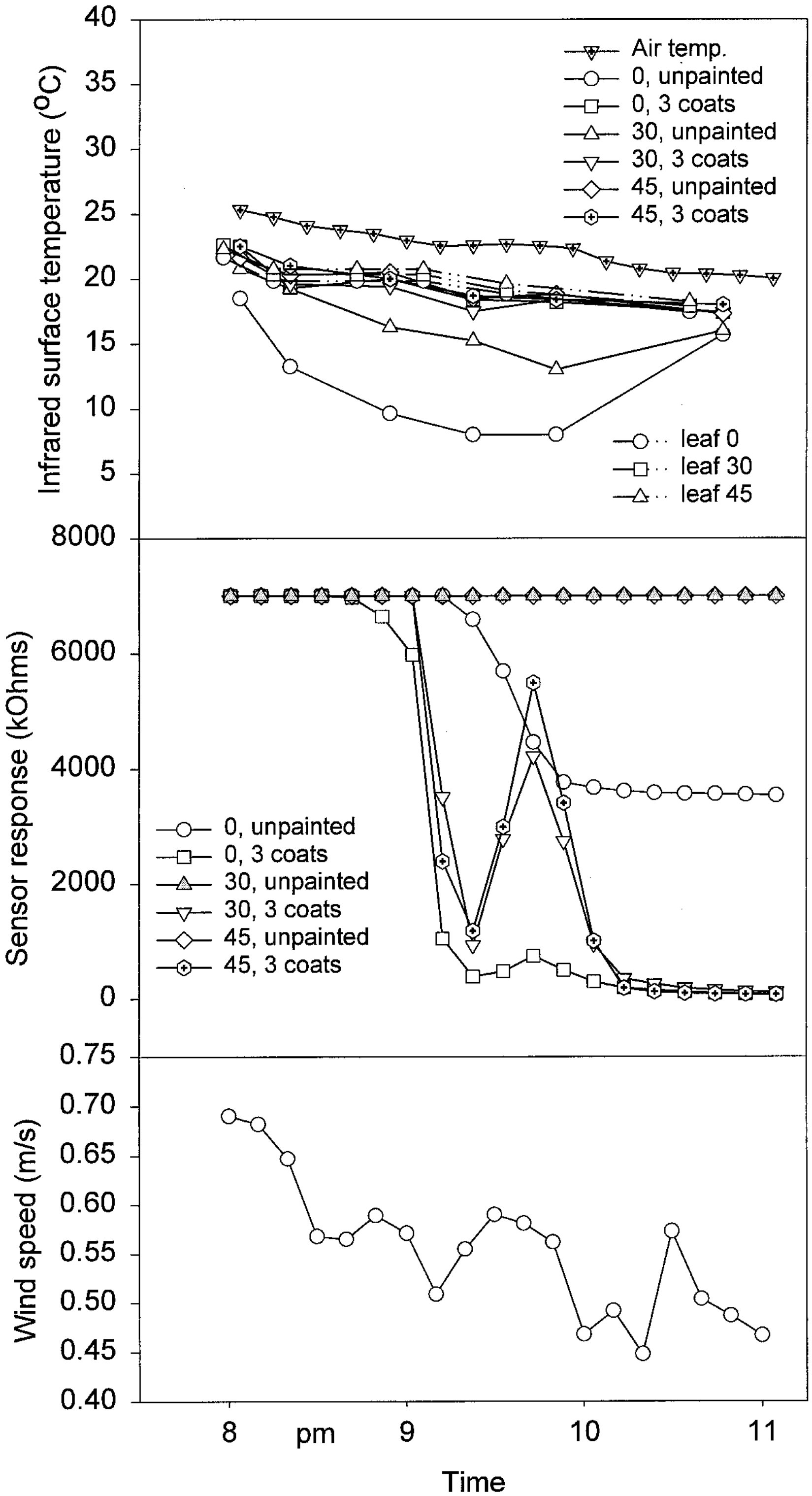

Fig. 2. Changes in **(A)** apparent temperature of tomato leaflets, wetness sensors, and ambient air; **(B)** electrical resistance (kΩ) of wetness sensors; and **(C)** wind speed during the onset of dew on 15 August. Sensor data are nonreplicated; leaflet data are means of two replicate leaflets. A low apparent temperature can indicate that an object is either cold or is not cooling by radiation. Radiation cooling of the unpainted sensors was minimal, and the infrared temperature was largely the reflection of background temperature, whether the background was tomato leaves (45° angle) or the cold night sky (0° angle).

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