Adding Plant Water Uptake Monitoring to a Low-Cost Wireless Multi-Sensor Data Aggregation Platform for Precision Agriculture

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Abstract.

Low-cost wireless sensor networks for precision agriculture are dominated by soil-side measurements such as moisture and pH, which are inexpensive and robust but cannot reveal how much water a plant actually takes up or whether it is under stress. Plant-based sensing, in particular dendrometry, provides a direct, non-destructive proxy for plant water status through diurnal stem shrink-and-swell cycles, yet most commercial plant-sensing instruments are expensive, proprietary, standalone systems that are difficult to fold into the multi-sensor networks growers already deploy. This work shows that plant water-uptake monitoring can be added to an existing low-cost aggregator through a modular software driver alone, with no changes to the platform's core firmware and at negligible marginal cost, and that pairing a plant-water-status sensor with soil sensing on co-located nodes in the same low-cost network yields information that soil measurement alone cannot provide. A micro-displacement dendrometer (MIJ-02-LMS, Environmental Measurement Japan) was integrated into the Data Gator, an open-source, solar-powered ESP32 sensor aggregator developed under Project SCARECRO at the University of Idaho; integration required only a sensor driver, one configuration entry, and one factory registration. The instrumented node was deployed in a commercial vineyard from August 2025 to present (approximately ten months), logging stem radius displacement alongside soil moisture and rainfall. The system captured a repeatable diurnal contraction-and-recovery cycle, clear stem swelling in response to rain, and greater stem shrinkage during high-heat periods consistent with transpiration outpacing uptake, confirming that the low-cost platform records valid plant behavior. Because the dendrometer and a co-located soil-moisture node logged to the same low-cost network on a common time base, soil water availability and plant water use could be related directly: soil moisture was inversely correlated with maximum daily shrinkage (Spearman $\rho = -0.36$, $p < 0.001$), and stem shrinkage was significantly greater on hot days than on mild days (mean maximum daily shrinkage 42.5 versus 35.3 µm; $p = 0.018$). The results demonstrate a practical, inexpensive path to extending soil-focused sensor networks toward a more complete picture of crop water status.

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Keywords. *Dendrometer, IoT field sensing, Wireless sensor network, crop water monitoring, ESP32 microcontroller*

Introduction

Precision agriculture increasingly relies on dense, low-cost in-field sensing to inform irrigation and crop management decisions. Most affordable monitoring systems measure soil-side variables, principally soil moisture and pH, because these sensors are inexpensive, robust, and simple to interface. Soil moisture alone, however, does not reveal how much water a plant is actually taking up or whether the plant is experiencing water stress: a given soil water content can correspond to very different plant responses depending on atmospheric demand, rooting, and crop physiology.

Plant-based water-status sensing offers the missing complement to soil measurements. Dendrometry, the measurement of micrometer-scale changes in stem or trunk diameter, is a well-established, non-destructive proxy for plant water status (Zweifel et al., 2001; Deslauriers et al., 2007). Stems contract during the day as transpiration draws on stored water and recover at night as water is replenished; the amplitude and timing of these cycles track plant water deficit and have been used as an irrigation-scheduling index in many woody crops, including grapevine (Goldhamer and Fereres, 2001; Intrigliolo and Castel, 2007).

The barrier to wider adoption is that commercial plant-sensing systems are typically expensive, proprietary, and standalone instruments. They are not designed to be folded into the heterogeneous, multi-sensor wireless networks that growers and researchers are already deploying for soil and environmental monitoring (Dafonte et al., 2024). As a result, plant-based and soil-based data are often collected by separate systems, complicating the direct comparison that is most informative.

The Data Gator, developed under Project SCARECRO at the University of Idaho (Wells et al., 2024), is a low-cost, solar-powered, open-source sensor aggregator built around the ESP32 microcontroller. It collects data from wired (analog and I2C) and wireless (Bluetooth Low Energy, BLE) sensors and transmits readings over WiFi/MQTT, with SD-card fallback logging. Its modular sensor abstraction is designed to accommodate new sensor types with minimal software change.

The objective of this work was to integrate a micro-displacement dendrometer (MIJ-02-LMS) into the Data Gator without modifying the platform's core firmware, and to evaluate whether soil and stem measurements collected on co-located low-cost nodes capture plant water uptake under field conditions. Demonstrating that a plant-water-status sensor can be added to an existing low-cost aggregator through a modular driver alone, and that the resulting co-located data reveal interpretable plant behavior, would show a practical, inexpensive path to more complete crop water-status monitoring.

Materials and Methods

The Data Gator Platform

The Data Gator is built on a DFRobot FireBeetle 2 ESP32 development board (DFRobot, Shanghai, China) mounted on a custom carrier board that provides regulated power switching, multiple analog sensor inputs, an SD-card slot, and a real-time watchdog timer. The node is powered by a solar panel and rechargeable battery for unattended field operation. Each device transmits readings over WiFi using MQTT and logs to an on-board SD card as a fallback (Fig. 1).

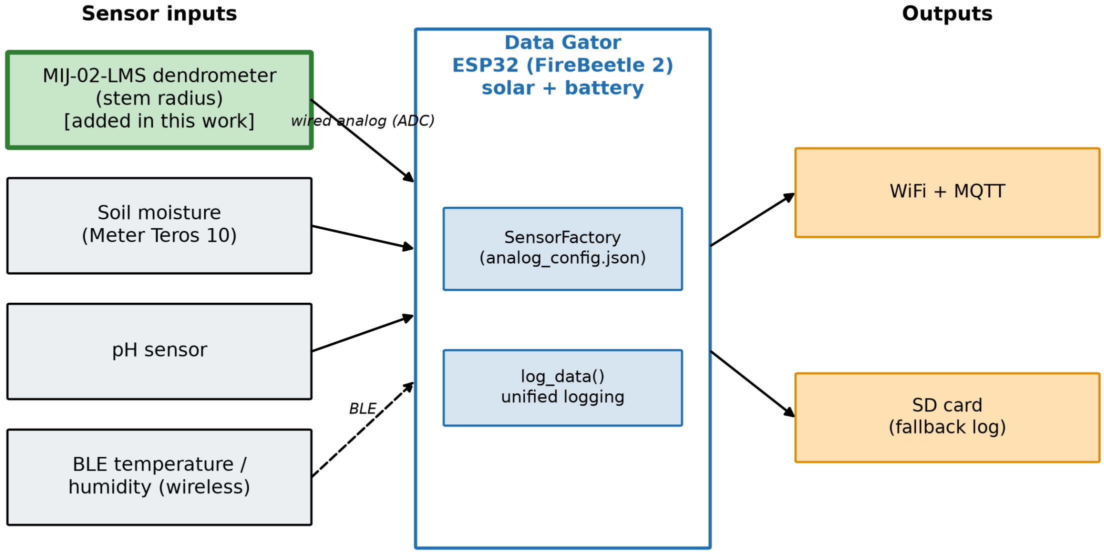

Figure 1 System architecture of the Data Gator node showing the soil-moisture, pH, BLE temperature/humidity, and dendrometer inputs feeding the ESP32 aggregator and the WiFi/MQTT and SD logging outputs, with the dendrometer addition highlighted

The firmware does not use the conventional Arduino infinite-loop model. Instead, the device follows a wake-and-hibernate duty cycle: on each wake, the device reads its sensors once, logs the data, and then hibernates for approximately 65 seconds before a watchdog reset begins the next cycle. This duty-cycle model is central to the platform's low power budget and determines the effective sampling interval in the field.

Sensors are handled through a sensor-abstraction layer. Analog sensors extend a common AnalogSensor base class, and a SensorFactory instantiates the configured sensors at boot from a JSON configuration file (analog_config.json) stored on the SD card. This design allows the set and arrangement of sensors to be changed per deployment by editing a configuration file rather than recompiling firmware.

Dendrometer Hardware

The plant-water-status sensor used was the MIJ-02-LMS micro-displacement dendrometer (Environmental Measurement Japan, Fukuoka, Japan). It uses a spring-loaded contact head and a hammer-head clamp to measure changes in stem radius non-destructively; the sensor is attached to the stem without piercing or girdling, making it suitable for season-long monitoring of living plants. The sensor presents a single-ended analog output over a three-wire interface (power, signal, and ground).

The dendrometer was mounted on the grapevine stem following the manufacturer's procedure (Fig 2), using the supplied sealing material, cable ties, and an initial spring tension to keep the contact head engaged through the stem shrink-swell range. The analog signal line was connected directly to the Data Gator's analog-to-digital converter (ADC) input on the carrier board and sampled in firmware; each dendrometer occupies its own ADC input.

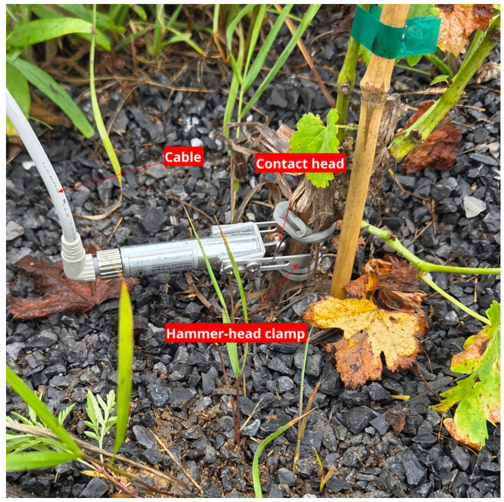

Figure 2 The MIJ-02-LMS dendrometer mounted non-destructively on the grapevine stem, with the contact head, hammer-head clamp, and cable labeled

Firmware Integration

Adding the dendrometer required only modular additions: a new sensor driver class, MIJ02LMS, that extends the AnalogSensor base class; a single entry in the SD-card ‘analog_config.json’ describing the sensor; and one case added to the SensorFactory so the factory can instantiate the driver. No lines of the core device firmware (scheduling, logging, communication, or power management) were modified. This modular-only integration is the central engineering claim of this work.

The driver converts the measured sensor output voltage to a stem radius displacement using the manufacturer's regression (Environmental Measurement Japan, n.d.), given here as Equation 1:

$$dr = 11000 * (Vout\ /\ Vpre) / (1 + \sqrt{2})$$

where dr is the radius displacement (μm), Vout is the sensor output voltage (mV), and Vpre is the excitation (preheat) voltage (mV). The firmware reads the ESP32 12-bit ADC (4095 counts at full scale), converts counts to volts and then to millivolts, and applies Equation 1. The preheat voltage was Vpre = 3.0 V (3000 mV), confirmed by repeated measurement during testing rather than assumed from the 3.3 V nominal rail.

Each wake cycle, the driver emits a reading as a JSON object containing the measured VOLTAGE (V) and the derived RADIUS (μm). This object is routed through the platform's single logging entry point, log_data(), which publishes it over MQTT and writes it to the SD card (Fig 3). Because the dendrometer reading flows through the same logging path as every other sensor stream, each reading carries a node identity and timestamp on a common time base; readings from co-located Data Gator nodes can therefore be aligned in time, which is what enables the direct soil-versus-plant comparison reported below.

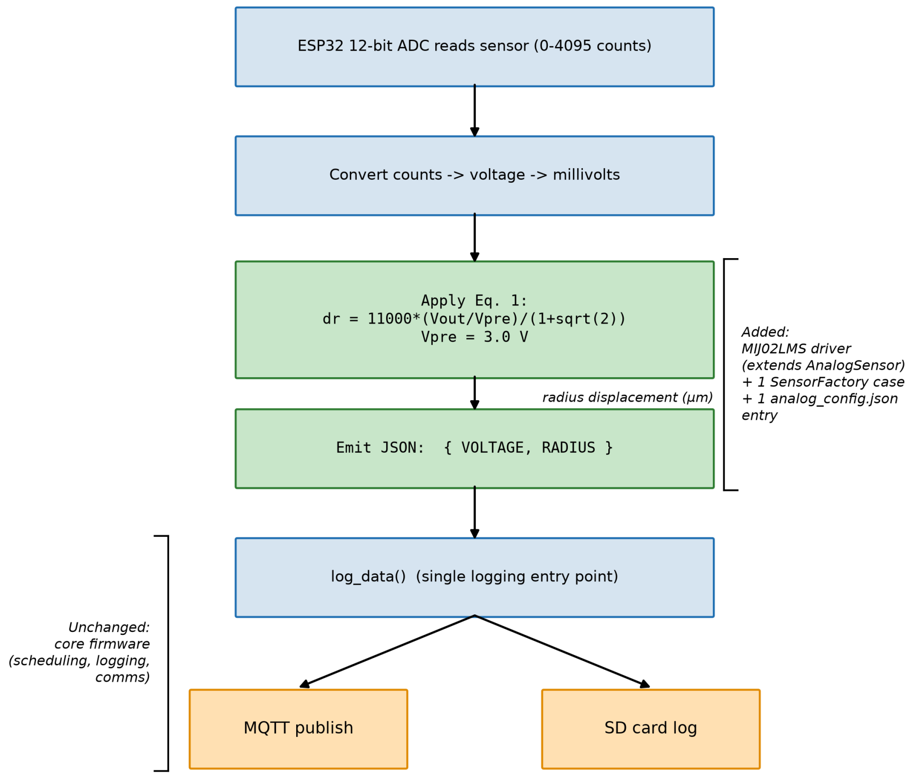

Figure 3 Data flow for the dendrometer: ADC counts to voltage to radius displacement via Equation 1, emitted as JSON and routed through log_data() to MQTT and SD, illustrating that only a driver and a configuration entry were added while the core firmware was unchanged

Field Deployment

The instrumented Data Gator node was deployed in a commercial vineyard at Laurel Grove Wine Farm in Winchester, Frederick County, Virginia, USA, in the Shenandoah Valley, from 19 August 2025 to 15 June 2026, a span of approximately 300 days. The monitored plant was an own-rooted Vitis vinifera 'Syrah' (clone 470) grapevine. Readings were taken once per wake cycle, giving an effective sampling interval of approximately 5.7 minutes; the primary dendrometer channel returned about 82% of expected samples over the deployment. The dendrometer Data Gator logged three analog channels, which were analyzed independently; results are reported for the primary channel unless noted.

Soil moisture was measured by a co-located Data Gator node (a separate device in the same low-cost network) carrying a TEROS 10 sensor (METER Group, Pullman, Washington, USA) reporting volumetric water content at three depths; the shared local time base allowed the soil and stem streams to be aligned for direct comparison. Rainfall and air temperature were obtained from a co-located WeatherFlow Tempest weather station, whose record begins in October 2025, so rain- and heat-response analyses cover October 2025 onward. Data reached the MQTT broker over WiFi; records were then retrieved, resampled to a uniform 15-minute grid, despiked with a Hampel filter, and time-aligned for analysis. Table 1 summarizes the node's sensor complement, and Table 2 describes the dendrometer and integration parameters.

Table 1 Sensor complement of the deployed Data Gator node

Sensor	Measured variable	Interface	Output unit	Sampling interval
MIJ-02-LMS dendrometer	Stem radius displacement	Analog (ADC)	µm (and mV)	~5.7 min
TEROS 10 (METER Group)	Soil volumetric water content	Analog (ADC)	m^3/m^3	~5.3 min
WeatherFlow Tempest	Rainfall, air temperature	Weather station	mm, °C	~5 min

Table 2 Dendrometer and firmware-integration parameters

Parameter	Value
Sensor model	MIJ-02-LMS (Environmental Measurement Japan, Fukuoka, Japan)
Compatible stem diameter	1.5–23 mm (manufacturer)
Excitation/preheat voltage (Vpre)	3.0 V (measured)
ADC	12-bit, 4095 counts full-scale (ESP32)
Resolution	1.22 µm per ADC count (Eq. 1, 12-bit ADC, 3.3 V ref)
Voltage-to-displacement conversion	Equation 1
JSON fields logged	VOLTAGE (V), RADIUS (µm)
Integration footprint	1 new driver class; 1 SensorFactory case; 1 analog_config.json entry; 0 core-firmware lines changed

Results and Discussion

The instrumented node operated through the deployment and produced a continuous record of stem radius displacement, with soil moisture and weather data being gathered on a common time base from the co-located Tempest and moisture sensor node. Over the approximately 300-day record, the primary dendrometer channel returned about 82% of expected samples on a 15-minute grid. The behaviors observed are summarized below, with quantitative values from the processed dataset.

Repeatable diurnal cycle. The stem radius record showed a clear, repeatable diurnal pattern of daytime contraction and nighttime recovery and swelling (Figure 4). This pattern is the expected dendrometric signature of plant water use and is the primary evidence that the integration captures real plant behavior in the field. Maximum daily shrinkage (MDS) averaged 39 µm (median 32 µm) and ranged up to approximately 187 µm; the daily maximum occurred near 07:00–07:30 (predawn) and the daily minimum near 13:30 (mid-afternoon), the expected timing for transpiration-driven stem contraction.

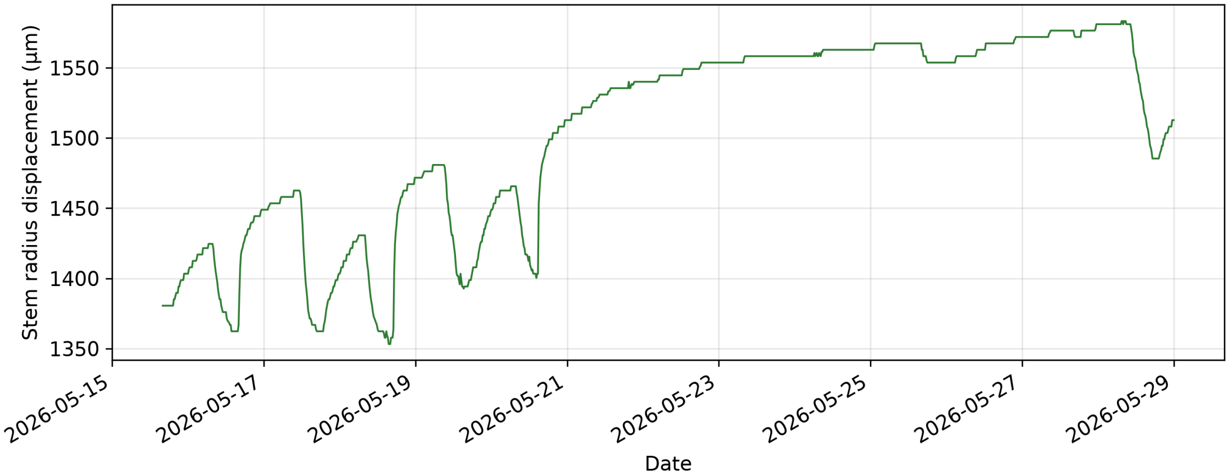

Figure 4 Multi-day time series of stem radius displacement (µm) for the primary dendrometer channel over a representative two-week window, showing the repeatable diurnal contraction and recovery cycle

Rain response. Rain events were clearly visible in the stem record as periods of swelling and baseline recovery (Figure 5). The magnitude and rate of recovery scaled with the amount of rainfall. Across the rain events resolved during the weather-record window (Table 3), post-event stem swelling ranged from a few micrometers to roughly 70 µm; larger or more sustained rainfall generally produced greater swelling and faster recovery, although the response varied across the ten events.

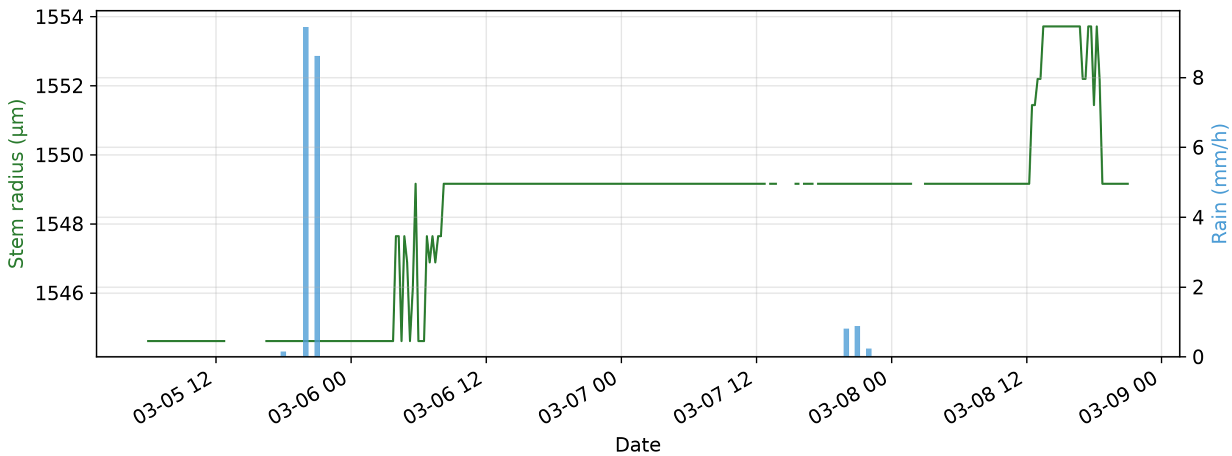

Figure 5 Stem radius displacement spanning the largest resolved rain event (18.2 mm, March 2026; rainfall on the right axis), showing post-event swelling and recovery

Table 3 Rain-event response on the primary dendrometer channel (selected events; October 2025–June 2026 weather window)

Event date	Rainfall (mm)	Post-event swelling (µm)	Recovery rate (µm/h)	Hours to peak
2026-03-05	18.2	9.1	0.14	67.5
2025-12-19	7.4	41.0	1.84	22.2
2026-01-10	5.0	41.0	0.80	51.0
2025-11-05	3.2	72.9	1.26	58.0
2026-05-27	9.9	11.4	0.84	13.5

Heat stress. During periods of high heat, the stem showed greater daily shrinkage than on milder days (Figure 6), consistent with transpirational demand outpacing water uptake. High-heat days were defined as those whose daily-maximum air temperature exceeded the 90th percentile of the record. On these days MDS was significantly larger than on milder days (mean 42.5 versus 35.3 μm; Mann-Whitney $p = 0.018$), consistent with greater water deficit under high evaporative demand; the duration of the daytime contraction phase did not differ significantly between hot and mild days ($p = 0.52$; Table 4).

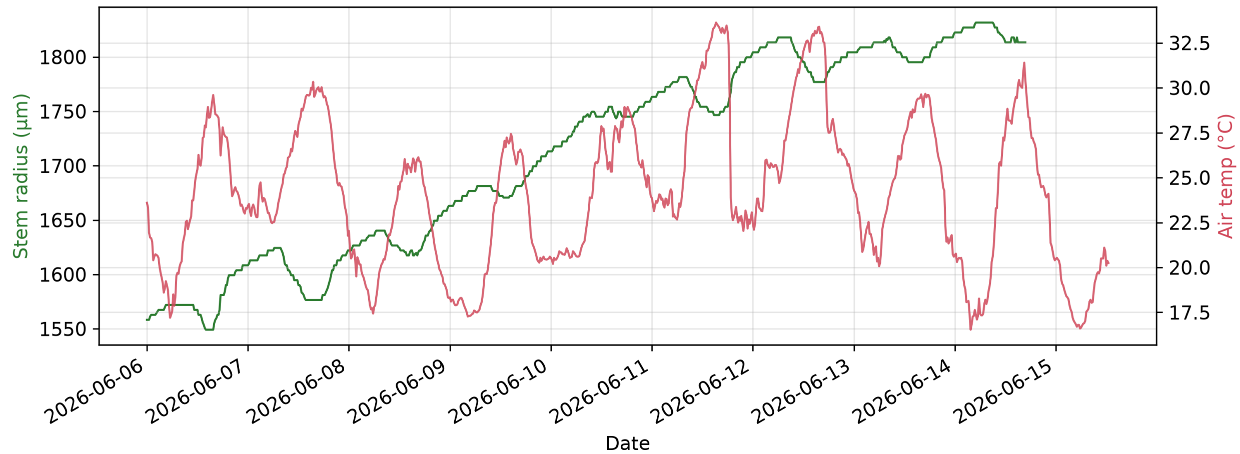

Figure 6 Stem radius displacement during a high-heat period (air temperature overlaid, right axis) showing greater daily shrinkage relative to milder days

Table 4 Heat-stress summary (primary dendrometer channel): hot days (daily maximum air temperature above the 90th percentile) versus mild days. MDS difference $p = 0.018$; contraction-duration difference not significant ($p = 0.52$); Mann-Whitney U

Period	Days	Mean MDS (μm)	Contraction duration (h)	Median daily-minimum time
Hot days	25	42.5	10.3	~13:30
Mild days	199	35.3	11.6	~13:30

Soil versus plant comparison. Because the dendrometer node and the soil-moisture node logged to the same network on a common time base, soil water availability and plant water use could be compared directly (Figure 7). This comparison is the principal contribution of the work: it links a soil-side variable that is easy to measure with a plant-side response that reflects actual water status. Daily soil volumetric water content (range 0.05–0.25 m^3/m^3) was inversely correlated with maximum daily shrinkage (Spearman $\rho = -0.36$, Pearson $r = -0.28$, both $p < 0.001$; Fig 7b) and positively correlated with the daily stem minimum (Spearman $\rho = 0.22$, $p < 0.001$): wetter soil corresponded to less daily stem shrinkage, the expected signature of reduced water stress.

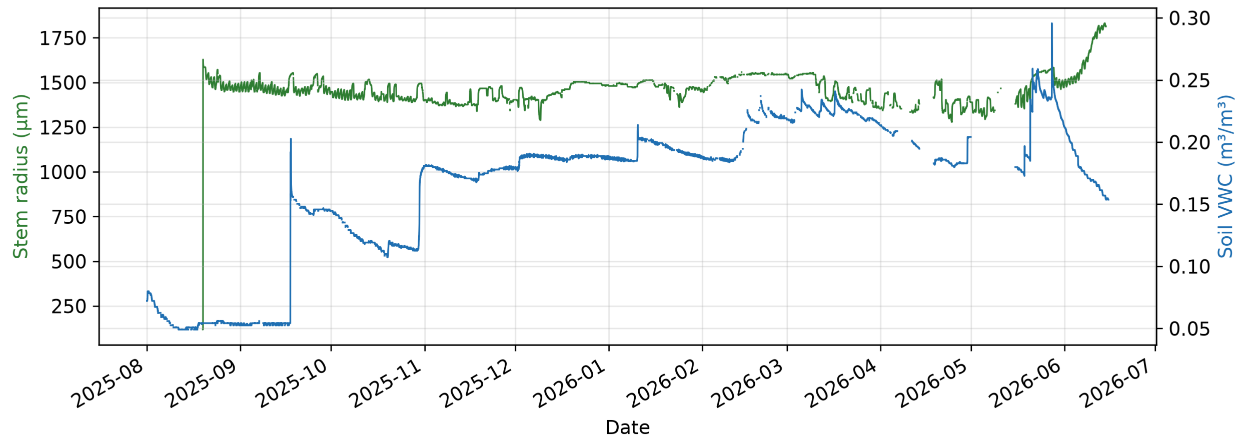

Figure 7 Co-located stem radius displacement (left axis) and soil volumetric water content (right axis) on a shared time axis, illustrating the relationship between soil water availability and plant water use from co-located nodes

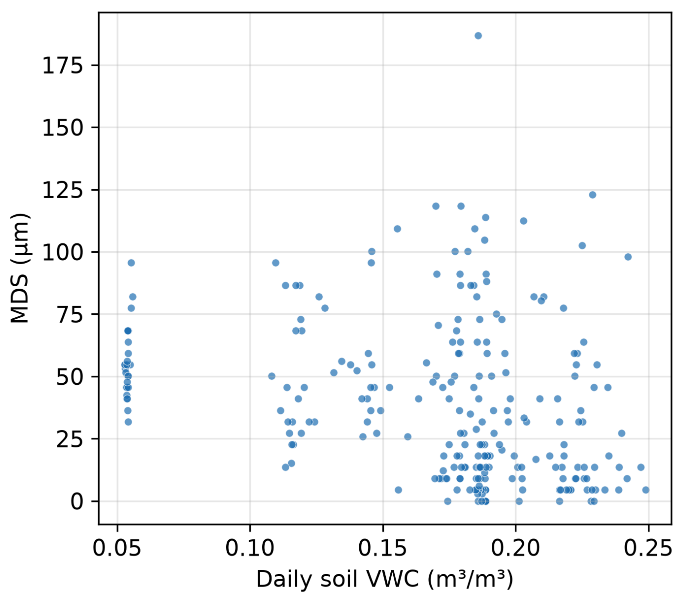

Figure 7b Daily soil volumetric water content versus maximum daily shrinkage (MDS); wetter soil corresponds to less daily stem shrinkage (Spearman $\rho = -0.36$, $p < 0.001$)

Taken together, these observations indicate practical value for irrigation scheduling and early stress detection from a single low-cost node. Several limitations should be noted. The results are preliminary single-node data without statistical replication. The dendrometer provides relative displacement rather than absolute calibrated stem diameter. Stem material and the sensor itself have some thermal sensitivity, so part of the apparent signal during large temperature swings may be thermal rather than hydraulic. These limitations motivate the further work outlined below but do not affect the central finding that the integration captures interpretable, physiologically consistent plant behavior.

Conclusion

This work integrated a micro-displacement dendrometer into the low-cost, open-source Data Gator wireless sensor aggregator and demonstrated three results from an approximately ten-month vineyard deployment. First, the low-cost platform captured valid plant-water-status data, reproducing the expected diurnal stem shrink-swell cycle and responding correctly to rain and heat. Second, and most importantly, co-locating the dendrometer with a soil-moisture node in the same low-cost network related soil water availability to plant water use directly, soil moisture was inversely correlated with maximum daily shrinkage (Spearman $\rho = -0.36$, $p < 0.001$), providing information that soil sensing alone cannot give. Third, this was achieved through a modular software driver with no changes to the platform's core firmware and at low marginal cost, making the approach adoptable at scale: adding plant-water-status sensing required only the MIJ-02-LMS sensor, about US$281 (¥45,000), integrated in software at no additional hardware or platform cost; with the roughly US$150 aggregator an instrumented node totals near US$430. Commercial micrometer-precision dendrometer logging systems, by contrast, cost about US$300–600 per sensor plus US$200–500 for a separate data logger, and US$1,000–1,500 or more for complete field-grade packages, so the integration delivers comparable plant-water-status sensing, co-located with soil data, at substantially lower cost. Together, these extend the Data Gator from soil and environmental monitoring to plant water-uptake monitoring, giving a more complete picture of crop water status than soil measurements alone.

These findings are based on preliminary single-node, single-season data, and are demonstrative rather than statistically conclusive. Further research includes multi-node and multi-season deployments with statistical replication, absolute calibration and temperature compensation of the dendrometer signal, automated stress-detection and irrigation triggers, and correlation of the stem signal with reference methods such as sap flow or evapotranspiration.

Acknowledgments

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