LEAF: Logger for ecological and atmospheric factors

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ABSTRACT

The fields of meteorology, surface- and groundwater hydrology, and forestry are often decoupled despite the fact that they occur simultaneously at the intersection of living systems and the physical environment. In this work, we describe a system that allows concurrent measurement of canopy throughfall, transpiration, air temperature, pressure, and humidity at multiple heights, in addition to soil moisture and several surface water parameters. LEAF is designed to be generalizable to many other hydrology and meteorology applications, and is modular such that it is easily adaptable for use with additional, diverse environmental monitoring sensors. This low-cost, light-weight, solar-powered system is capable of simultaneous streaming telemetry as well as local data logging via SD card.
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1. Hardware in context

Environmental parameters, particularly meteorological and hydrological data, are crucial for understanding Earth systems [1]. Improved global data coverage has aided this by enabling further model development and evaluation [2–6]. Land-atmosphere exchange models continue to become increasingly complex in order to simulate higher-resolution physical processes, such as inter-species variation in vegetation behaviors [7,8], which often have profound effects on ecosystem-scale functionalities [9,10]. The associated data requirements are similarly increasing in density, specificity, and spatiotemporal resolution. Current developments to the surface-atmosphere component of the Community Earth System Model (CLM and CESM), used for the prediction of future climate scenarios by the Intergovernmental Panel on Climate Change (IPCC) [11,12], include multiple vertical levels of resolved within-canopy microphysics (CLM-ml v0 [13]) and plant functional

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type-scale vegetation-water dynamics [14]. Such model developments are presently at the limits of or are increasingly out-pacing our ability to collect the high-quality within-canopy measurements required to facilitate such advances [13,15].

The high cost and power requirements of standard commercial sensing equipment constrain our ability to make such measurements at the required spatiotemporal densities, especially in remote locations and in areas where infrastructure is either prohibited or unavailable [16–18]. Here we present an environmental sensing system that is small, low-cost (Table 1, Table 2, and Table 3), solar powered, and easily customizable (Table 5) for a broad variety of environmental applications. The system was designed to provide data to three disparate but collocated projects, which required the simultaneous assessment of tree canopy throughfall, transpiration, within-canopy physics, and surface- and groundwater interaction.

This project's three goals were to (1) assess the influence of vertical leaf area distribution on the timing and variability of canopy throughfall, (2) evaluate the vertical profile of transpiration within a tree crown and its feedbacks with localized temperature and humidity, and (3) determine the amount and timing of tree-, soil-, and stream-water interaction within a riparian zone. Each of the project's facets require a different set of measured parameters recorded in the same locations both within and below the canopy. The within-canopy version of the sensing system was designed to be small and lightweight enough to be easily and quickly mounted to branches without causing damage to the tree, while the below-canopy version was designed to be robust enough to withstand potential flooding. Each system was equipped to monitor precipitation, air temperature, air pressure, humidity, and sap flux (as a proxy for transpiration rate). Branch-mounted systems were equipped with accelerometers to monitor for branch motion, and below-canopy systems were further augmented to measure soil moisture and temperature, stream temperature, water depth, and turbidity.

This project requires networks of sensing systems that are distributed vertically and mounted on branches as small as six inches in diameter and at heights up to 40 m above the ground. Designs were further constrained by the requisite number of measurement locations, cost of each system, and the requirement that each be rugged enough to be field-deployed indefinitely with little to no direct maintenance. Capabilities of sensors manufactured in-house are similar to those of commercially available devices from companies such as Meter, Campbell Scientific, LiCOR, ONSET, and Dynamax, but at substantially lower cost and, in some instances, size and weight (Tables 2 and 3). It is important to note here, however, the difference between "DIY cost" and "commercial cost" (Table 3). Commercial cost is inclusive of parts, labor and research and development, while the presented DIY cost does not include labor costs and should be considered strictly a materials budget.

Table 1
Specifications table.

Hardware name	LEAF: logger for ecological and atmospheric factors
Subject area	Hydrology, Meteorology, Geosciences, Ecology, Agriculture
Hardware type	Field measurements and sensors
Open Source License	CC-BY-SA
Cost of Hardware	$275/node, $1300 for system as described
Source File Repository	https://zenodo.org/record/3407772#.XaCfcUZKibg

Table 2
Data logger comparison table.

Vendor	Model	Cost	Power	Communication
Particle	Electron	$69.00	5v	Cellular
National Instruments	cRIO-9037	$6761.48*	24v	Ethernet/Wireless
ONSET	RX3003-SYS-KIT-80X	$2099.00*	SOLAR-5 W	Cellular
Campbell Scientific	CR310-CELL200	$1347.50*	12v	Cellular
Meter	ZL6	$650+$180/yr	12v	Cellular
LiCor	LI-7700	$24,900	12v	Wireless
Dynamax	GP2	$2195.00	10-15v	SaIP Wireless
PCE Americas Inc	PCE-KD3-WGH	$682.00	24v	USB
Omega	OM-LGR-5325	$1585.00*	9v	USB

Table 3
Sensor comparison table.

Sensor	DIY Cost	Commercial price range
Temperature and humidity	$4-$9	$126-$486
Atmospheric pressure	$2-$12	$640-$779
Sap flux	$2	$184-$300
Accelerometer	$5-$25	$1294-$1338
Soil moisture	$3-$9	$250-$400
Stream temperature	$5-$22	$92-$117
Water depth	$3-$27	$771-$828
Turbidity	$13-$26	$3540

2. Hardware description

This system was developed to gather data in a manner that is usually prohibitive using low-cost commercial dataloggers: polling multiple types of sensors with various output modalities at different rates and resolutions. Many low-cost, commercial data-logging systems permit integration with only a select suite of sensors operating on a particular communication protocol. The adaptability of the microcontroller in LEAF allows environmental sensors to be incorporated as needed, regardless of their communication protocol. Each sensing system, or 'node', is equipped with a single microcontroller capable of logging all sensors (Table 5) for a fraction of the cost normally associated with logging (Table 2).

LEAF is capable of storing logged data locally on a microSD card and remotely through telemetry. The logger can transmit data directly to Google Sheets or to a more specialized data ingestion portal such as the new Cloud-Hosted Real-Time Data Service (CHORDS) system of the National Center for Atmospheric Research (NCAR) [19]. Redundant recording capacity is crucial for data-loss prevention in locations where power or connectivity loss may occur. Standard commercial microSD cards are used for local storage to enhance ease of use and serviceability in place, rather than using proprietary data download hardware or systems that require uninstallation and reinstallation in the field.

The lack of available power infrastructure at our study location mandated that the power subsystem be included in the design. Power considerations are not typically present in measurement system designs and left to the discretion of the user. This system was designed to be fully integrated including a solar power source and battery backup.

Differentiating aspects of the LEAF system design include:

- Modular design for incorporation of sensors with different communication protocols
- Integrated solar power system facilitates use in remote locations
- Local and telemetry-based data logging
- Low-cost, low-power, and low-weight to allow deployment in remote and challenging locations

3. Design files

Table 4.

4. Bill of materials

See BoM file on Zenodo repository: https://zenodo.org/record/3407772#.XaCfcUZKibg [20]
Note: quantities in BoM refer to the number of units (sets) purchased, not to individual parts.

5. Build instructions

These instructions are for the specific use of the technology described in this paper. However, the system can be generalized and expanded to monitor other environmental variables through the incorporation of additional sensors. For a brief list of examples, see Table 5.

Table 4
Design files summary.

Design file name	File type	Open source license	Location of the file
Circuit Schematic	EAGLE CAD File	CC-BY-SA	https://zenodo.org/record/3407772#.XaCfcUZKibg
Board	EAGLE CAD	CC-BY-SA	https://zenodo.org/record/3407772#.XaCfcUZKibg

Circuit Schematic: This is an EAGLE.sch file detailing the circuit diagram for the Sensor Nodes.
Board: This is an EAGLE.brd file with one possible board layout for the Sensor Nodes.

Table 5
Included and optional sensors for the LEAF system.

Included	Optional
Soil and temperature	Anemometer
Water depth	Snow water equivalent
Water temperature	Snow depth
Turbidity	Water flow rate
Accelerometer (branch)	Stream pH
Rain gauge	Solar radiation (and within canopy light)
Sap flux	Photosynthetically active radiation
Air temperature and humidity	Leaf wetness
Atmospheric pressure	

6. Tools

- Soldering iron
- #2 Phillips screwdriver
- Hot glue gun
- Screw gun
- Small flat blade screwdriver
- Drill
- ¼" drill bit
- Step drill bit
- Rasp
- Lug crimping tool
- Wire stripper
- Wire cutter
- Blacklight
- Vacuum chamber
- Multimeter
- Alligator clip leads

7. Battery box

1. Attach the terminal strips to the inside of the lid of the plastic ammo can using machine screws and nuts.
2. Cut six small notches (~1/2″) under the lip of the container to allow cables to pass through.
3. Attach jumper wires for the positive and negative terminal strips using fork connectors.
4. Crimp two female spade connectors to the ends of a piece of speaker wire approximately 1 ft. long, and two fork connectors to the other end, one on each conductor.
5. Attach the positive fork to the positive battery terminal on the solar charge controller, the negative fork to the negative battery terminal on the solar charger, and the respective spade connectors to each terminal of the lead acid battery.
6. Place the battery in the container.
7. Attach the positive load terminal of the charge controller to the positive terminal strip, and the negative load terminal of the charge controller to the negative terminal strip.
8. Attach positive leads (white) to positive terminal strip, and negative leads (black) to negative terminal strip (Fig. 1).

8. Rain gauge

1. Open the rain gauges and remove the preinstalled circuit boards.
2. Solder one wire to each end of the reed switch (the glass capsule in the middle of the board) on the rain gauge circuit board.

Fig. 1. .Assembled ammo-can battery box deployed in Hilo, Hawai'i. Shown with lid open.

3. Drill a hole in the bottom of the rain gauge for the wires to pass through.
4. Pass the wires through the hole, replace the circuit board, and close the rain gauge.
5. Cut wire mesh to fit across the top of the rain gauge and hot glue in place to act as a leaf guard (Fig. 2).
6. Drill two holes in the end of the plank that the gauge will be mounted on, spaced for the holes on the base of the rain gauge, and mount it with two machine screws and nuts.

9. Sap flux sensor

1. Follow directions for custom thermal dissipation sensor manufacture as in Granier [21] (Fig. 3)
2. Attach a power supply (such as the 12 V battery) to the input + and - side of the buck regulator (flux sensor power supply board), and a multimeter in DC volts mode to the other side, then adjust the potentiometer until the output voltage reads 2.00 V.
3. Solder conductors from a 4-conductor cable of sufficient length to reach the tree trunk or branch from the sensor node to the + and - thermocouple leads, and the two leads of the heater.

10. Turbidity sensor

1. Solder conductors from a 4-conductor cable of sufficient length to reach water from the ground unit to the OUT, LED, VCC, and GND pins of the color sensor.
2. Solder a jumper between S0, S1, and VCC.
3. Solder a jumper between S2, S3, and GND.
4. Pot the sensor using clear epoxy, clearing the bubbles by degassing in the vacuum chamber (Fig. 4).

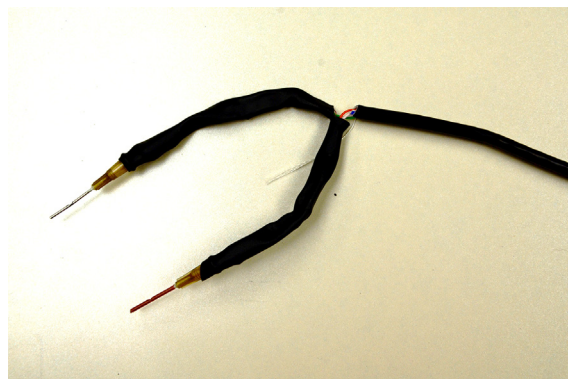**Fig. 2.** Tipping bucket rain gauge shown with wire mesh cover and cable modification.

Fig. 3. Thermal dissipation-style sap flux sensor.

Fig. 4. Epoxy potted turbidity sensor.

11. Water depth sensor

1. Solder conductors from a 4-conductor cable of sufficient length to reach a point above, yet out of the water to the TRIG, ECHO, VCC, and GND pins of the ultrasonic distance sensor from the ground unit.
2. Cover the back of the depth sensor board with conformal coating or epoxy (Fig. 5).

12. Sensor nodes

1. Fabricate a carrier board for the Electron using protoboard as shown in Fig. 7 below. Use four 19-pin long female 0.1″ headers to create a socket for the Electron and its attachment points, a 6-pin long male 0.1″ header to create an attachment point for the OpenLog, and a 0.1″ or two-pin screw terminal.
2. Solder wires into the four contacts of the relay board.
3. Attach the coil wires of the relay to pins GND (−) and D4 (+).
4. Attach the switch wires of the relay (A and B) to the +12 V line and the heater input line.
5. Drill a hole and add a wire bulkhead cable gland to the enclosure.
6. Affix the Electron carrier board inside of its enclosure.
7. Pass the power cable through the cable gland.
8. Attach the power cable to the VIN and GND pins of the carrier board, positive to VIN and negative to GND, respectively.
9. Pass rain gauge wires through the cable gland.
10. Attach accelerometer to lead wires and feed the wires through the cable gland.
11. Attach the 3 V3 wire for the accelerometer (ST LSM9DS1) to the 3 V3 pin, the GND wire to the GND pin, the SCK wire to the D1 pin, and the SDA wire to the D0 pin.
12. Attach the DHT22 humidity and temperature sensor to pin D2, 3 V3, and GND, and its 4.7 kΩ pull-up resistor to 3 V3.
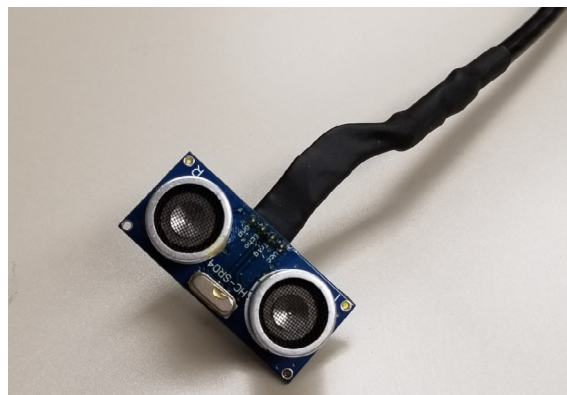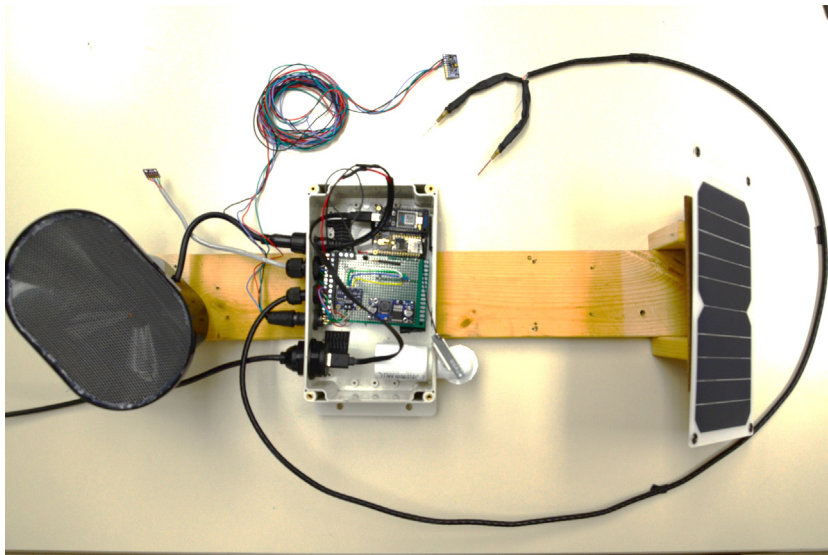

Fig. 5. Ultrasonic depth sensor.

Fig. 6. Assembled node for branch mounting. Control box is shown with lid off for clarity.
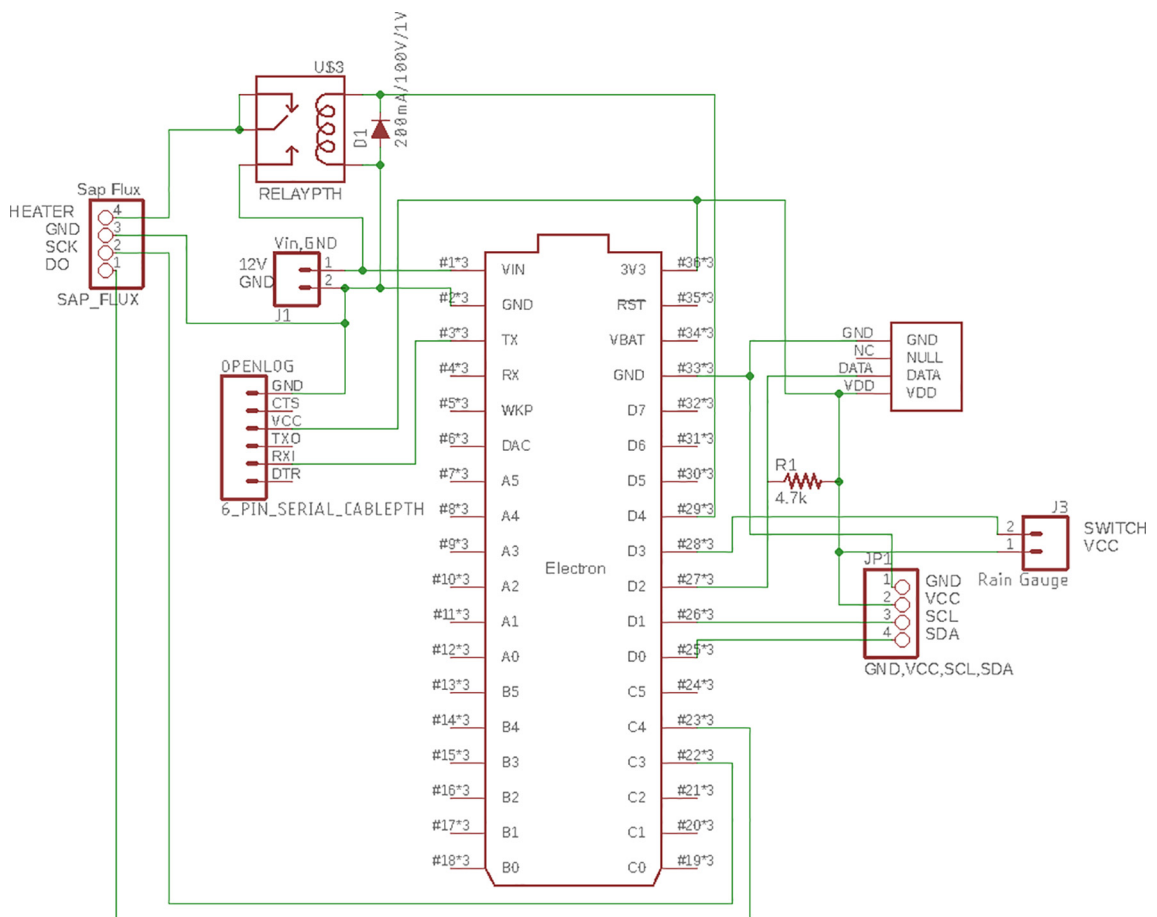

Fig. 7. Sensor Circuit - Electrical component diagram of the sensors connected to the Particle Electron microcontroller.

13. Feed the sap flux sensor leads through the cable gland into the enclosure.
14. Attach the sap flux sensor heater leads to its power supply board.
15. Attach the sap flux sensor thermocouple leads to the thermocouple amplifier board.
16. Attach the leads from the sap flux sensor power supply board to the +12 V, GND
17. Attach the thermocouple amplifier board pins to the+ and − leads from the thermocouple.
18. Attach the SCK pin from the thermocouple amplifier and ADC to C3, MISO to C2, and MOSI to C1 pins on the Electron carrier board.
19. Connect the thermocouple amplifier CS pin to GND. Fig. 6 shows completed unit.
20. Repeat all of the above for the other two tree-mounted units and the ground unit.

Complete the following for only the ground unit

1. Feed the turbidity and temperature sensor leads through the cable gland.
2. Attach the turbidity sensor VCC lead to 3 V3, GND to GND, LED to D4, and OUT to A2.
3. Attach the temperature sensor leads: red to 3 V3, black to GND, and yellow to D7 and the 4.7 k resistor.
4. Attach the other end of the 4.7 kΩ resistor to 3 V3.
5. Feed the depth sensor lead through the cable gland.
6. Attach the depth sensors VCC lead to 3 V3, GND to GND, TRIG to D5, and ECHO to D6.
7. Feed the soil moisture sensors' leads through the cable gland.
8. Attach the soil moisture sensors' VCC leads to 3 V3, GND to GND, and AOUT leads to A3, A4, and A5, respectively.
9. Attach a 100 kΩ and 10 kΩ resistor to one another, and attach their connection to A6.
10. Attach the other leg of the 100 kΩ resistor to VIN.
11. Attach the other leg of the 10 kΩ resistor to GND.
21. Power the Electron using its USB port or the power cable to register and configure it following the directions on the Particle website or App.
22. Open the build.particle.io web IDE.
23. Copy and paste or upload the main code (SensorNode.ino) from the Zenodo file repository into the web IDE interface.
24. Flash this code to the sensor node. Repeat for the other tree-mounted nodes.
25. Copy and paste or upload the ground unit code (SensorNode_Ground.ino) from the GitHub repository into the web IDE interface.
26. Upload this code to the ground unit node using Particle's build page (build.particle.io).

13. Characterization and calibration

Characterization and calibration of the unit must be completed before deployment. Required calibration procedures are as follows:

13.1. Tipping bucket calibration

13.1.1. Materials

- 100 mL graduated cylinder
- 1 L beaker

The tipping bucket rain gauge requires 0.02 in. of rain depth for every tip, and has a funnel area of 30.95 in^2 per the manufacturer's specifications. This can be verified by the following procedure:

1. Pour in ~11 mL of water by gently spilling it down the inside of the funnel and make certain that the tipping bucket tips.
2. Pour 1 L of water in the same way as above, and make certain that the tipping bucket flips 99 to 100 times.

13.2. Temperature sensor calibration

- Ice
- Water
- Beaker
- Balloon or Ziploc bag
- Thermometer

For the temperature sensors, use the following procedure

1. Place the temperature sensor in the balloon or bag.
2. Place the balloon or bag into an ice water bath (0 °C standard) in the beaker while monitoring the temperature. Record the temperature and output when it has stabilized.
3. Take the balloon or bag out of the ice bath and remove the sensor.
4. Record the temperature and output once stabilized to room temperature (∼20 °C standard).
5. Hold the temperature sensor in hand or under an arm until it equilibrates to body temperature (∼36 °C standard).
6. Record the temperature and output once stabilized to body temperature.

13.3. Accelerometer calibration

13.3.1. Materials

- Level
- Playing cards
- Flat steel plate
- Magnets

13.3.2. Calibrate the accelerometer by the following procedure

1. Lay the level on the plate, then rotate it 90° to make certain the surface is level in both axes. If not level, shim underneath it with playing cards at the corners.
2. Place the accelerometer flat on the sheet and pin it with a magnet.
3. Record the accelerometer output ($ax = 0$ g, $ay = 0$ g, $az = 1$ g).
4. Rotate the accelerometer 90° so that its short edge is touching the sheet, and pin it in place with both magnets.
5. Record the accelerometer output ($ax = 0$ g, $ay = 1$ g, $az = 0$ g).
6. Rotate the accelerometer 90° so that its long edge is touching the sheet, and pin it in place with both magnets.
7. Record the accelerometer output ($ax = 1$ g, $ay = 0$ g, $az = 0$ g).

13.4. Soil moisture sensor calibration

Follow the calibration method given by METER Group Inc [22].

13.5. Water depth sensor calibration

Materials
- Measuring tape
- Flat board or panel greater than 1 ft^2 in area

Calibrate the depth sensors by the following procedure
1. Pull the measuring tape out and place it on the floor, locked.
2. Place the board at the end of the measuring tape standing on end to present its largest surface area to the depth sensor.
3. Record the output from the depth sensor at 0.5 ft increments both going towards and away from the board.

13.6. Turbidity sensor calibration

Follow the procedures outlined by the Washington State Department of Health [23].

14. Hardware installation

1. Mount the sensor nodes and hose clamps on pieces of wood.
2. Mount and level the wooden carrier board.
3. Install sap flux sensor into branch/trunk following standard directions (see [24] for details).
4. Mount accelerometer to a tertiary branch securely with zip ties.
5. Run power cables down the tree to the battery box. Attach cables to the tree using staples.
6. Terminate power cables with fork lugs.
7. Attach fork lugs to their respective terminal strips.
8. Place solar panel in open sunlight, oriented properly for maximum insolation based on geographic location.
9. Attach solar panel leads to their respective leads on the solar charge controller. (See Figs. 8–10).

15. Cloud Streaming Setup

1. The Particle Electron ships with five items. Ensure all five are available.
a. Particle Electron Microcontroller
b. Particle cellular SIM card
c. Antenna with IPEX connector
d. USB A to Micro B cable
e. LiPo Battery with female JST connector
2. Using a web browser, navigate to https://setup.particle.io
3. Setup a Particle user account, if one has not yet been established. This one account can be utilized for several devices. Also note added security for the device, through the use of "Two-Factor Authentication". It is highly recommended by the vendor to utilize "Two-factor Authentication" for Particle devices. See: https://docs.particle.io/tutorials/developer-tools/two-step-authentication/#setup
4. On the "Welcome to Particle" screen select "Electron / E Series", then "Electron", and click "Next".
5. A screen titled "Enter your SIM's ICCID number" contains a form field in which you must enter the numbers listed under the barcode on the Particle SIM card. When completed, click "Next". [Note: You will need to provide credit card information to which the selected data plan will be charged.] Follow instructions at: https://docs.particle.io/tutorials/cellular-connectivity/sim-management/#data-plans
6. Remove the microSIM card using the perforated edges and insert it into the SIM slot located on the bottom of the Electron. The side with the gold connectors should face the Electron.
7. Attach the antenna to the white u.FL connector on the Electron.
8. Plug the female JST connector on the LiPo battery into the male JST connector on the Electron.
9. The Particle Electron will flash green until a connection is made to a local cell tower at which point the light will turn cyan and pulse in a breathing like manner every three seconds. If the Particle Electron does not enter the "breathing cyan" mode, further support from Particle.io may be required.
10. At this point the assigned Particle.io user account will "claim" the device and ask for a personalized name. Enter one into the form field and click "Next".
11. After a brief set of tutorial slides, click "Start Building" to complete the setup.

Uploading the LEAF firmware on to the Particle Electron using the Particle Dev Desktop IDE:

Note: There are several ways to perform this action depending on preference. This methodology will concentrate on use of the Particle Dev Desktop IDE.
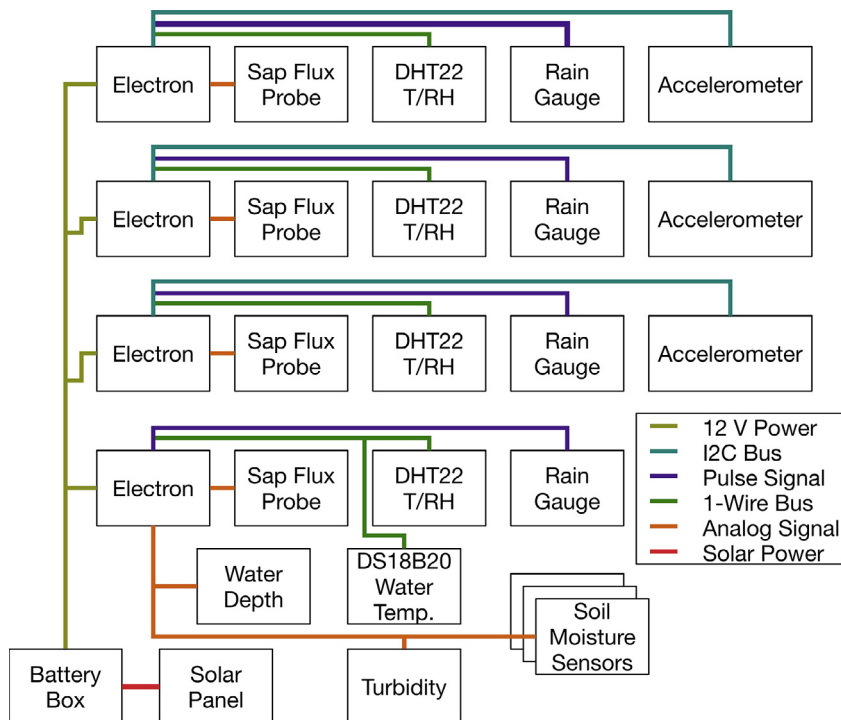

Fig. 8. System wiring diagram for three branch-mounted sensing systems and one base-of-tree system.

1. Download the LEAF source code from the software repository and expand the compressed ".zip" file.
2. Navigate to https://docs.particle.io/tutorials/developer-tools/dev/#download and then download/install the appropriate version of "Particle Dev" for your computer.
3. Open the "Particle Dev" application and select "Particle" from the menu bar.
4. Select "Log in to Particle Cloud" and authenticate with the Particle user account associated with your device.
5. Again select "Particle" from the menu bar and click "Select Device".
6. Choose the Particle Electron device previously setup.
7. Click "File" and "Add Project Folder"
8. Navigate to the directory that contains the ".ino" file associate with LEAF. The directory should contain both an ".ino" file and a "project.properties" file. If both are not in the directory, code compilation errors related to the libraries may occur.
9. Click the "Compile in cloud and show errors if any" icon on the left panel. The icon resembles a cloud with a check mark. If errors occur, they must be corrected prior to flashing your device.
10. Click the "Compile in cloud and upload code using cloud" icon on the left panel. The icon resembles a lightning bolt.
11. A notification that cellular data will be used will display. If agreed, click the "Flash OTA Anyway" button.
12. The Particle electron will quickly flash a "purple" led before returning to the "breathing cyan" state.
13. At this point the Particle Electron is ready to transmit data.
14. Verification of operation can be assessed by navigating to https://console.particle.io, selecting "Devices" and then clicking your device. Logged startup messages will then display in the "Event Logs" window.
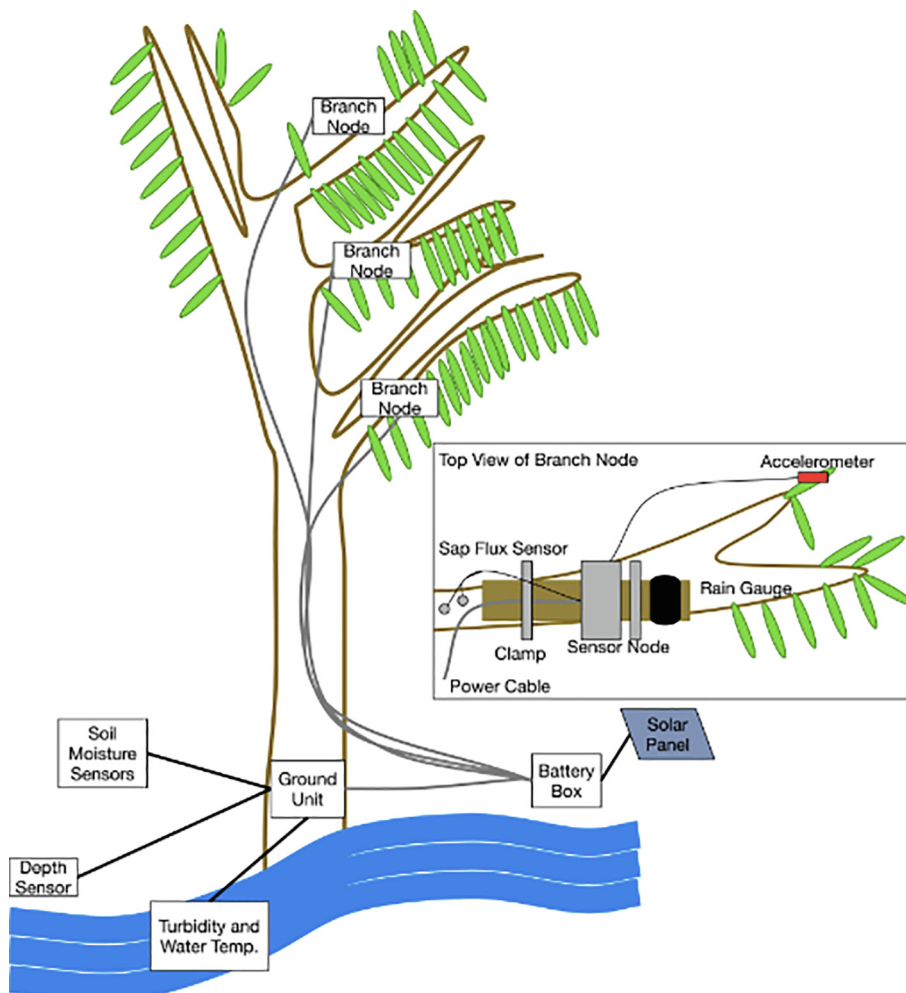

Fig. 9. System deployment diagram. Drip loops are recommended between the trunk of the tree and the battery box.

16. Validation

The first revision of LEAF was deployed inside the canopy of a Macadamia tree (*Macadamia integrifolia*) on the eastern slope of the Big Island of Hawai'i, approximately 10 km NNE of Hilo. Soil moisture sensors were buried at 5 cm, rain gauges were deployed within the tree canopy at approximately 12, 16, and 20 ft. above ground. A ground unit containing T and RH sensors was deployed at the base of the tree (Figs. 8–10).

Fig. 10. Installed branch node. Sap flux sensor (left of the rain gauge) is shown without reflective covering to show detail.
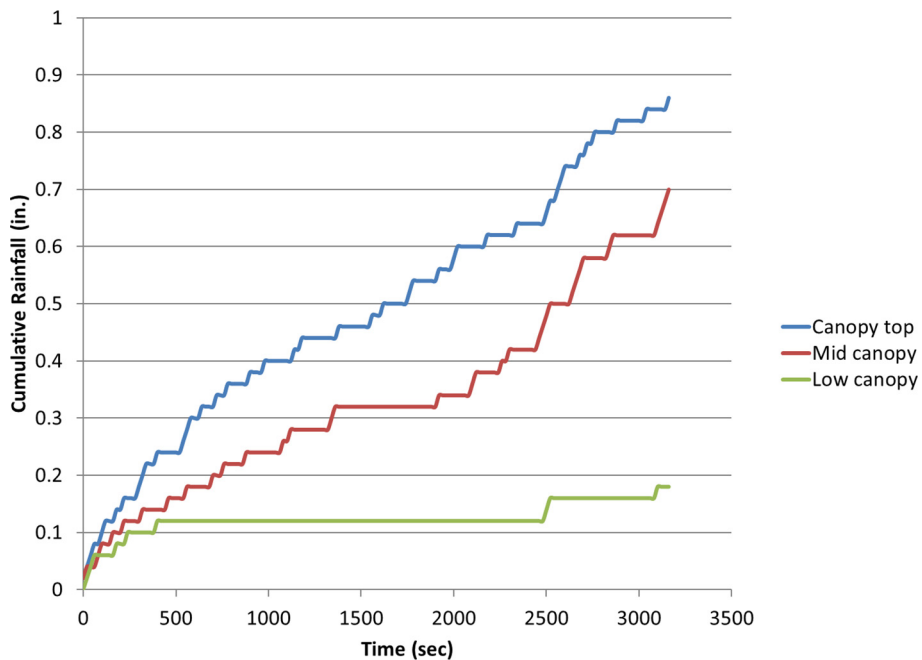
Fig. 11. Precipitation through the canopy (throughfall) at 20 ft (Canopy top), 16 ft (Mid canopy), and 12 ft (Low canopy) above the ground. Canopy leaf area prevents much of the throughfall from reaching lower canopy layers.

Rainfall recorded on August 10th, 2018 by within canopy rain gauges demonstrated the influence of leaf area density to reduce the amount of canopy throughfall (Fig. 11). The stair step pattern in the data is reflective of the 20 s recording interval set for the tipping bucket rain gauges. Daily air temperature profiles typically ranged from 20 °C to 31 °C (Fig. 12). Diurnal patterns in temperature reflect daily patterns of solar radiation with a maxima slightly after solar noon. Local maxima and
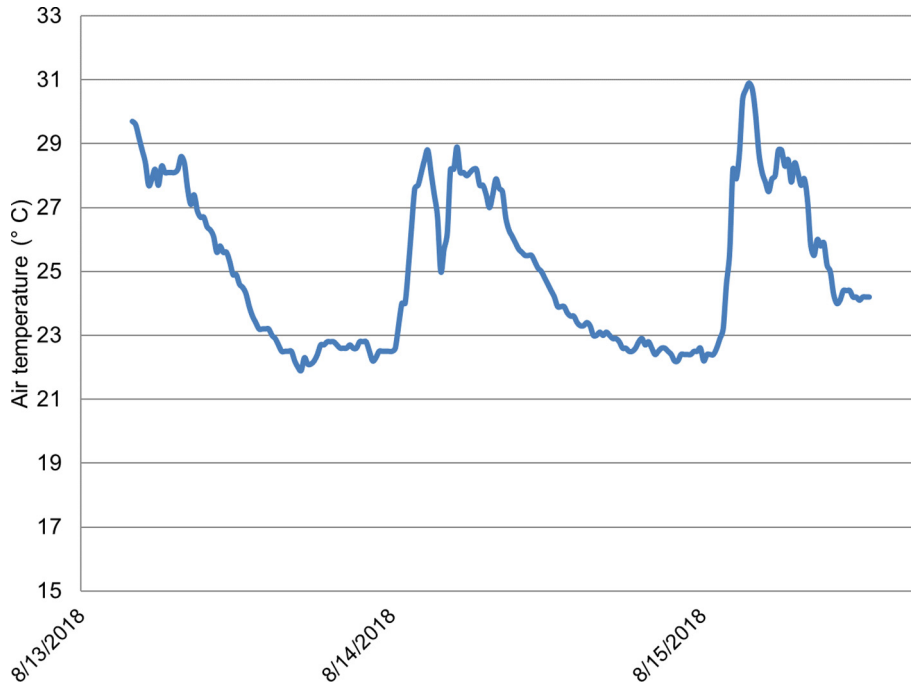

Fig. 12. Sub-canopy air temperature ranged between 20 and 31 °C reflecting the tropical climate of Hawai'i.
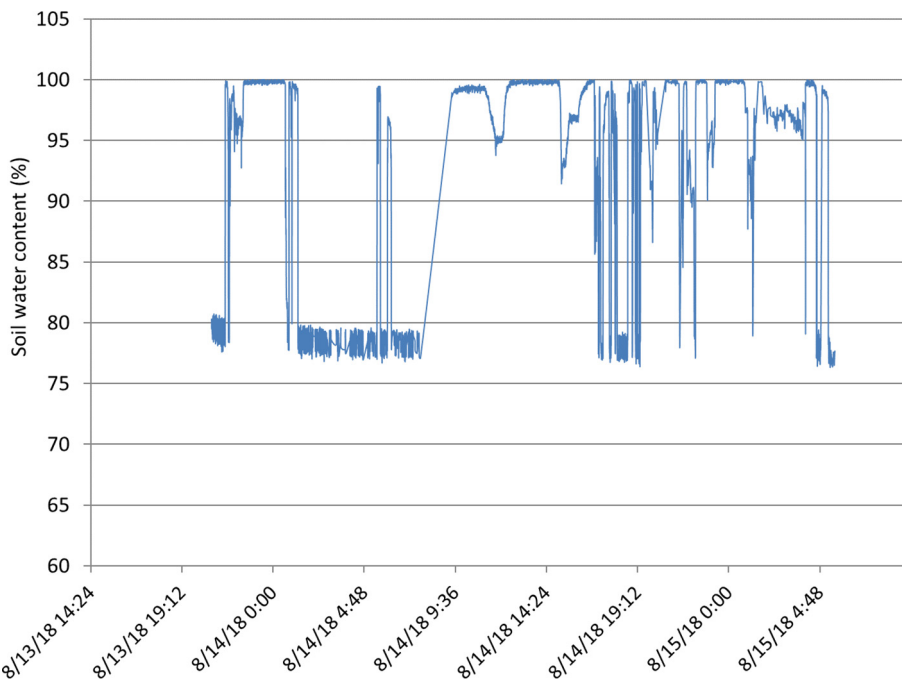

Fig. 13. Soil moisture (measured by conductivity) at 5 cm depth under the leaf litter at the base of the tree. Times are in UTC.

minima during the day are frequently caused by wind and passing cloud cover. On days where precipitation occurred, such as August 14th, 2018 commensurate declines in temperature were recorded.

Shallow soil moisture (5 cm depth) responds quickly to atmospheric demand for water vapor and precipitation (Fig. 13). However, high-frequency variation (i.e. sub-half hourly) in soil moisture data can be considered measurement noise and filtered using a moving average or similar technique to smooth. Similar measurement noise is also seen in data using commercial sensors.

During validation, the system performed as expected. On occasion, cellular network outages resulted in gaps in on-line data streams. However, data was backed-up locally through the microcontroller's SD card. LEAF systems were not adversely affected by high temperature, high humidity, or precipitation. The level of insolation at the test deployment site was commensurate with the needs of the system power budget such that no data-loss due to power outage was observed.

17. Capabilities

- Solar charging allows for continuous operation for periods of >4 h of insolation per day.
- Internal storage for each node of 16 GB allows for years of local data storage.
- Entire system is remotely programmable, allowing firmware updates, changes in sampling period or data target service, and sensor calibration or configuration.
- Modular configuration facilitates the addition of new nodes or sensors, without requiring a full-system reconfiguration.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Peter Marchetto has an active collaboration with Particle on using their products in research applications. Je'aime Powell is currently engaged in collaboration with Particle through their Particle for Good initiative.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ohx.2019.e00079.

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