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PRACTICAL TOOLS

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Measuring microenvironments for global change: DIY environmental microcontroller units (EMUs)

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Abstract

1. Rapid climate change is generating an urgent need to understand how organisms respond to environmental variation. Understanding these responses at an organismal level requires environmental data at finer spatial and temporal scales than is available from global datasets. Current measurement technologies force a trade-off between collecting data at the broad spatial scales relevant to global change while simultaneously capturing environmental variation at the fine spatial and temporal scales relevant to organisms. The greatest hurdle to ameliorating this trade-off is the cost of commercially available sensors.
2. Here, we introduce environmental microcontroller units (EMUs), data loggers designed and built to accurately measure fine-scale variation in temperature, humidity, light, and soil moisture at low cost. We detail how to construct EMUs, test their utility in measuring microenvironment under field settings, and compare their accuracy to commercial data loggers in the same field setting.
3. Parts for EMUs cost less than $20 per unit; an order of magnitude less than comparable commercial loggers. Their cost-effectiveness allows for many more units to be deployed to measure microenvironment, providing the capacity for broader spatial sampling. Their programmability and modularity make them flexible, and they can be quickly assembled using unskilled labour.
4. Using EMUs in a field setting, we detected microenvironmental variation in temperature, humidity, irradiance, and soil moisture at scales of <80 m. Despite their affordability, EMUs were of comparable accuracy to that of commercial sensors.
5. With the growing availability of inexpensive microcontrollers and hobbyist electronics, the time is ripe to tap into the versatility and computational power of do-it-yourself electronics to address critical ecological questions. In addition to marked cost advantages, EMUs are both more flexible and more capable than most commercial options, providing the tools to bypass the trade-off between the extent and resolution of environmental measurement. Yet, their simple design makes constructing them feasible for ecologists without specialist backgrounds in electronics.

KEYWORDS
climate change, data loggers, ecological sensors, EMUs, ESP8266, microclimate, microcontrollers, microenvironment

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1 | INTRODUCTION

Conserving ecological systems under rapid climate change requires an understanding of how environmental change impacts the growth, development, distribution, and evolution of organisms (McLaughlin et al., 2017; Urban et al., 2016). Organisms respond to the local microenvironmental conditions they experience, not large-scale mean conditions (Bramer et al., 2018; Suggitt et al., 2011), but data are rarely available at sufficient spatiotemporal resolution to characterize the relationships between microenvironmental conditions and the responses of individual organisms (Ashcroft & Gollan, 2012; Kennedy, 1997). Instead, global datasets focus on broad patterns at coarse spatial resolutions due to trade-offs between cost and resolution. There is an increasing need for fine-scale environmental data to feed into mechanistic models of the climatic responses of organisms (Bramer et al., 2018; Urban et al., 2016).

Commercial data loggers such as iButtons (Maxim Integrated) and Hobos (Onset Computer) (Table 1; see Bramer et al., 2018 for review) are capable of measuring local environmental conditions at broad spatial scales (e.g., Ashcroft & Gollan, 2013), but cost, in particular, limits their utility for large-scale microenvironmental research (reviewed in Bramer et al., 2018). Given that the most inexpensive temperature and humidity data loggers typically cost $70–100 (Table 1), scaling up to many data loggers represents a substantial financial investment. Incorporating measurement capabilities for additional environmental variables such as light or soil moisture increases costs to $500–1000/unit (Table 1). In addition, commercial data loggers often fail permanently in field conditions, with reported failure rates of 7%–27% (Anderson et al., 2015; Ashcroft & Gollan, 2013; Lebrija-Trejos, Pérez-García, Meave, Poorter, & Bongers, 2011; Lewkowicz, 2008). Many do not have replaceable batteries or parts or cannot be repaired, thus limiting their life spans. Most data loggers have limited data memory and can only store several thousand measurements, forcing trade-offs between temporal resolution and duration.

An emerging alternative to expensive commercial loggers are do-it-yourself programmable microcontroller units (e.g., Arduino™, http://arduino.cc) and sensor modules that can accurately measure environmental conditions (Baker, 2014; Beddows & Mallon, 2018; Ingelrest et al., 2010; Miller & Dowd, 2017; Wickert, 2014). Their programmability and modularity make them flexible, since researchers can control the software, configure various sensors, store more data, and choose their power source. While these microcontroller units have been used to gather research data, we posit that their cost-effectiveness allows for deployment of many units to measure microenvironment, allowing better spatial sampling and mitigating a limitation of microenvironment research (Bramer et al., 2018).

TABLE 1 Cost and accuracy comparisons between environmental microcontroller units (EMUs) and commercial sensors. EMUs are less expensive than any commonly used commercial data logger, and a comparable HOBO system measuring the same variables costs 50× more. For commercial sensors, resolution and accuracy are those reported from data sheets. Readings refers to the number of sensor measurements that can be stored in the data logger's memory

Data logger/Unit	Sensor	Resolution	Accuracy	Readings	Cost
EMU with temperature, humidity, solar radiation, and soil moisture					$17.00
	ESP8266 Microcontroller	N/A	N/A	80,000[a]	$3.50
	BME 280 Temperature	0.01°C	0.5°C		$2.75
	BME 280 Humidity	0.008% RH	3% RH		$2.75
	BH1750FVI PFD	22 μmol m^{-2} s^{-1}[b]	51 μmol m^{-2} s^{-1}[b]		$0.95
	Generic Soil Moisture Probe (VWC)	2.2e-5 m^3/m^3[b]	0.078 m^3/m^3[b]		$0.40
Hobo with temperature, humidity, solar radiation, and soil moisture					$850.00
	H21-USB Microstation Data logger	N/A	N/A	85,000	$231.00
	S-THB-M008 Temperature/Humidity	0.02°C	0.21°C		$195.00
	S-THB-M008 Temperature/Humidity	0.1% RH	2.5% RH		$195.00
	EC-5 Soil Moisture Sensor	0.0007 m^3/m^3	0.02 m^3/m^3		$139.00
	S-LIA-M003 PAR sensor	2.5 μmol m^{-2} s^{-1}	5 μmol m^{-2} s^{-1}		$220.00
	RS3-B Solar Radiation Shield	N/A	N/A		$65.00
iButton Temperature/Humidity	Hygrochron DS1923	0.0625°C	±0.5°C	2,048	$79.00
Hobo Pendant Temp/Light 8K				3,500	$47.00
	Temperature	0.14°C	± 0.53°C		
	Light*	N/A	N/A		
LiCor LI250 Light Meter	LI-190R	*c.* 0.1 μmol m^{-2} s^{-1}	*c.* 4 μmol m^{-2} s^{-1}	N/A	$1,145

[a]Number readings stored as CSV for EMUs, based on Lolin D1 mini flash capacity. Data could be stored more efficiently.
[b]Resolution and RMSE accuracy from laboratory calibrations (see methods).
*Hobo Pendants only report relative light levels and are strongly biased by UV.

Here, we describe environmental microcontroller units (EMUs) built to measure microenvironmental variation in temperature, humidity, light, and soil moisture. We provide detailed instructions and code to allow assembly in an ecology laboratory setting by researchers or students without prior experience with electronics. We compare EMUs to commercial data loggers and field test them to assess their performance.

2 | DESCRIPTION OF THE EMU

Environmental microcontroller units consist of a microcontroller "computer" that is programmed to periodically measure and record data from an array of connected sensors. In contrast to previous DIY microcontroller builds based on the Arduino™ (Baker, 2014; Beddows & Mallon, 2018; Miller & Dowd, 2017; Wickert, 2014), EMUs use the ESP8266 microcontroller (Espressif Systems, Pudong, Shanghai, China) as part of the Lolin D1 Mini (http://www.wemos.cc). The ESP8266 is faster and possesses better features than the Arduino™: a higher CPU speed (80 Mhz vs. 16 Mhz), more RAM (*c*. 43 KB vs. 2 KB), built-in WiFi, and more flash storage space (512 KB–16 MB vs. 32 KB), eliminating the need for an SD card. We used prototyping breadboards, plugging in wires and components to build the circuit powering the EMUs (Figure 1, Supporting Information Video S1, Table S1). Breadboard rows and columns are numbered and lettered, providing a simple way to copy the circuit without any electrical engineering experience (Supporting Information Video S1, Table S1). The non-permanent nature of breadboards allows for easy repair or reconfiguration (Baker, 2014). The timekeeper was a battery-backed DS3231SN real time clock (Maxim Integrated, San Jose, CA). To minimize battery usage, we used the clock's built-in alarm pin to turn on a P-MOSFET switch at each logging interval, supplying power to the EMU for only *c*. 5 s while logging, minimizing battery drain.

We used open-source NodeMCU firmware (http://nodemcu.readthedocs.io) for the ESP8266 microcontroller. This firmware provides a filesystem, interactive Lua command prompt, and allows Lua scripts to be run. In addition to NodeMCU, the ESP8266 can also be programmed in Micropython, or using the Arduino IDE. We found, however, that NodeMCU provided the best support and features. Step-by-step instructions for building the EMUs are available (Video S1) and code and additional instructions are available on Github (https://github.com/mickley/EMU).

2.1 | Sensors

Our current EMU setup is capable of measuring a number of terrestrial microclimatic variables evaluated in previous studies (e.g., Ashcroft & Gollan, 2013; Lebrija-Trejos et al., 2011) using sensors and sensor modules detailed in Table 1. We used a BME280 (Bosch Sensortek, Kusterdingen, Germany) for temperature and relative humidity (RH). To prevent direct solar radiation from affecting temperature and relative humidity measurements from the BME280, we built a radiation shield out of an inverted plastic cup bottom (Figure 1; Cowles, Wragg, Wright, Powers, & Tilman, 2016). For light, we used a BH1750FVI (ROHM Semiconductor, Kyoto, Japan). This sensor has a spectral response of 400–720 nm, peaking between 470 and 650 nm, that provides a good approximation (see below) of photosynthetically active radiation (PAR), as measured by a photon flux density (PFD) sensor. Soil moisture was

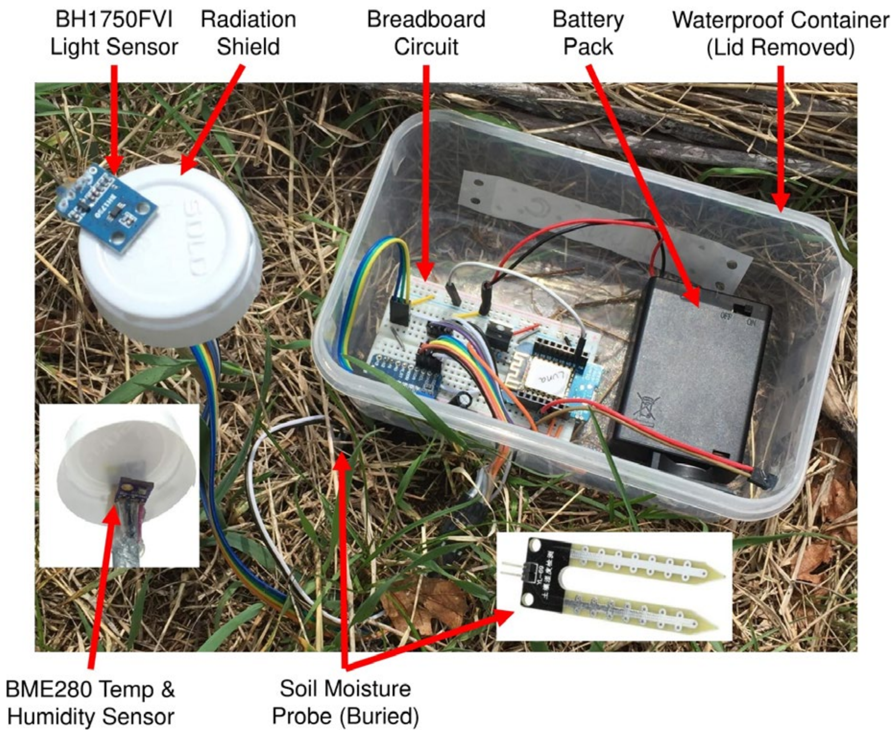

FIGURE 1 An environmental microcontroller unit (EMU) deployed in the field. Insets show the BME280 temperature/humidity sensor hidden underneath the radiation shield and the soil moisture probe that is buried in the ground

measured using generic resistive two-pronged probes connected to an ADS1115 analog to digital converter (Texas Instruments, Dallas, TX) that converts voltage from the probes into a 15-bit number that can be calibrated to soil volumetric water content (VWC). Since both the light and the soil moisture sensors did not natively measure PFD or VWC, we calibrated these against known standards (Supporting Information Section 4, Figures S1 and S2). Environmental microcontroller units' measurements were logged to a CSV file that can be downloaded to a computer via USB.

The entire unit was powered using four standard AA batteries. With the exception of the external sensors (temperature/humidity, PFD, and soil moisture probe), all of the electronics were housed in a plastic container with a gasketed lid. These containers have previously been field tested (Guevara & Mickley, 2017), and provide excellent low-cost waterproofing. A hole was drilled in the side of the containers to allow wires to pass through and sealed with hot glue. The total materials cost of our sensor units was less than $20, including all sensors and components, considerably less expensive than commercial solutions (Table 1). Costs associated with hours required to assemble units (using previously untrained students) were approximately $20 per unit, although there is an economy-of-scale when large numbers of EMUs are produced. A parts list, with costs and sources, and further building instructions are available on Github (https://github.com/mickley/EMU).

3 | PERFORMANCE TEST

Environmental microcontroller units were field tested in the UConn Forest (41.82517, −72.23813) for 3 weeks (30 May 2017 to 20 June 2017). The site is a floodplain meadow ranging from wetland to mesic

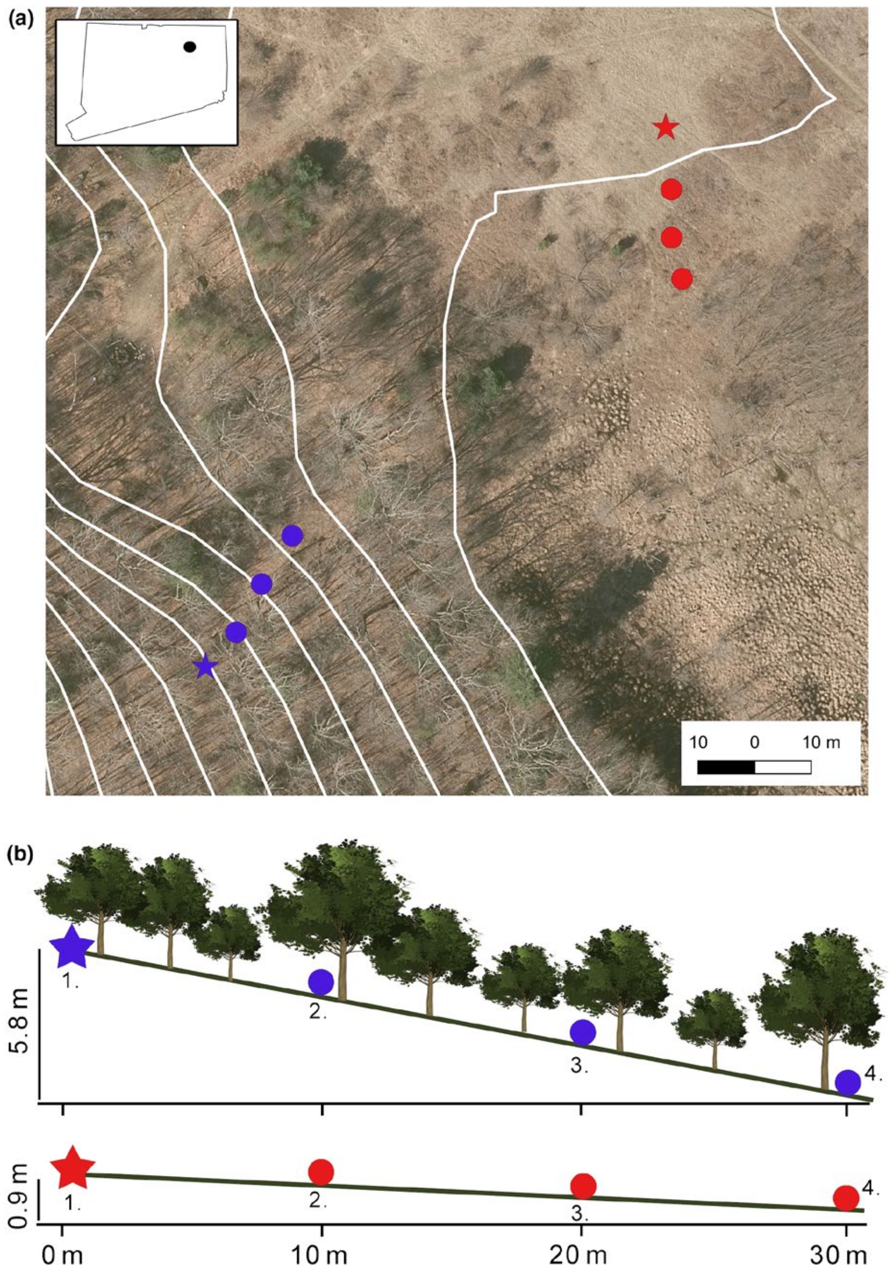

FIGURE 2 A depiction of our two transects. (a) Aerial imagery* with superimposed *c*. 1.5 m contours showing the meadow transect in red transitioning from meadow to wetland and the woods transect down a wooded hillside in blue. (b) The elevational gradient for the two transects. Stars represent the beginning of transects, and numbers correspond to those in Figure 3. *Retrieved from http://cteco.uconn.edu/data/flight2016/index.htm

woods. Eight EMUs were deployed at 10-m intervals along two 30-m transects (four per transect); one transect in an open meadow along a *c.* 0.9 m elevational gradient, the other *c.* 80 m away in woods with an elevational gradient of *c.* 5.8 m (Figure 2). EMUs were configured to take measurements every 15 min. For comparison, in addition to the EMUs, a HOBO Pendant® (UA-002-08, Onset Computer) measuring temperature was deployed with each EMU along transects, and a Hygrochron™ iButton (DS1923, Maxim Integrated) measured temperature and humidity at the beginning of each transect.

4 | RESULTS AND DISCUSSION

The EMUs detected fine-scale spatiotemporal environmental variation (Figure 3, Supporting Information Section 5.3, Tables S2, S3) with accuracy comparable to commercial alternatives (Supporting Information Figures S1–S3), but cost an order of magnitude less (Table 1). In addition to being accurate and low cost, their "plug-and-play" nature provides control of sensor selection (Supporting Information Section 3.3), offering greater flexibility and reparability than commercial sensors. Users can program the timing and frequency of measurements, on-board calculations of additional variables (Ashcroft & Gollan, 2013), and potentially, control of external research equipment based on measurements (e.g., automatic watering). Thus, the simple, flexible, and low-cost design of EMUs is applicable to a wide range of fields, settings, and applications.

After accounting for temporal trends, models indicated that field transects differed significantly for all environmental variables (Figure 3, The woods transect was cooler (1.98 ± 0.80°C), more humid (4.21 ± 1.55% RH), had lower light (300.69 ± 13.43 μmol m^{-2} s^{-1}), and had a soil VWC that was drier (0.14 ± 0.02 m^3/m^3). Significant differences were also detected between sampling points within transects (<30 m apart) for humidity, VWC, and PFD, but not for temperature (Figure 3). We captured considerable temporal variation, both within and among days (Supporting Information Figure S4).

Over the time interval, 88.6% of all possible data points were logged successfully. All of the missing data were due to moisture-related failure of a single EMU, or due to temporary sensor failures (Supporting Information Sections 3.2 and 5.5). Battery current draw was *c.* 20 mA for 5 s while measuring, and <10 μA between measurements, for theoretical AA battery life of up to 2 years measuring every 15 min. Temperature and humidity measurements using our EMUs corresponded strongly to those from iButtons and Hobo Pendants at the same locations (Supporting Information Figure S3;

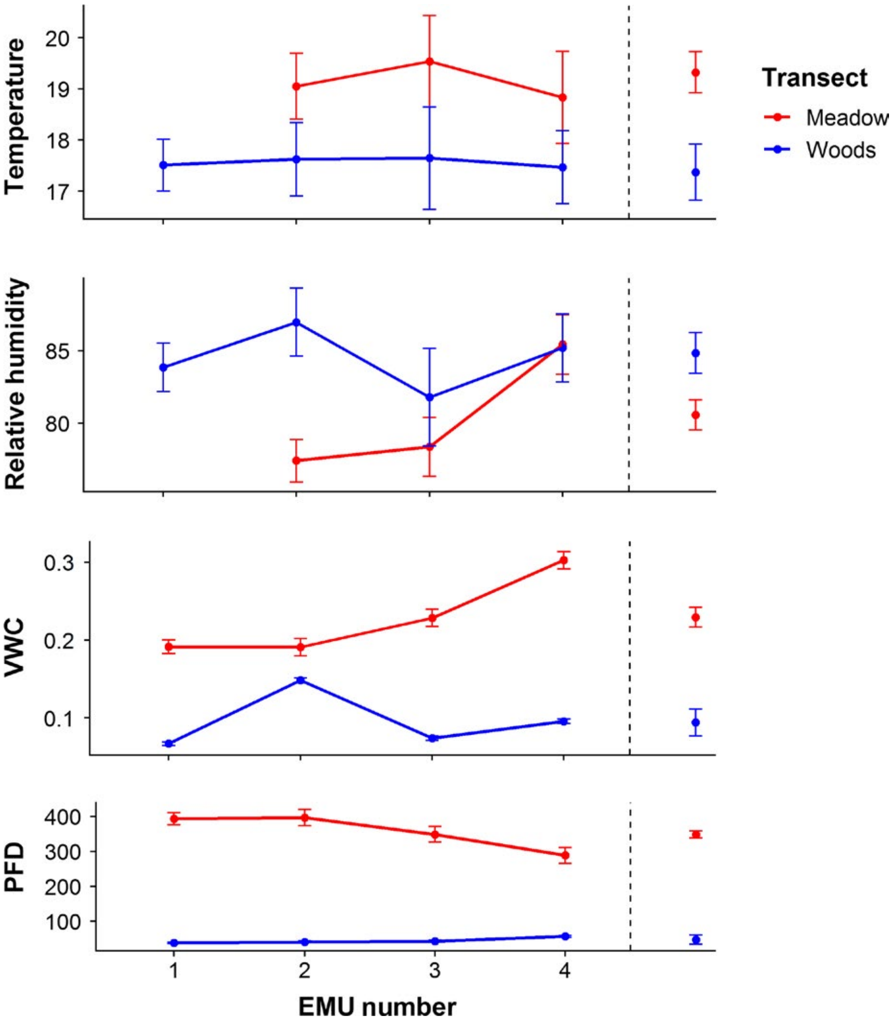

FIGURE 3 A comparison of the microenvironmental variation detected within and between transects. Points and error bars represent model coefficients and their standard errors from generalized additive mixed models run separately for each transect, with transect position as a fixed factor (*within*-transect differences). Points separated by the dashed line denote coefficients and standard errors from a generalized additive mixed model containing transect identity as a fixed factor (*between*-transect differences). For all four environmental variables, differences between transects are in the directions expected *a priori* (see also Supporting Information Tables S2,S3). Temperature and humidity data for one environmental microcontroller unit (EMU) were excluded from this and other analyses due to suspect readings prior to failing completely (Supporting Information Section 5.5)

iButton vs. EMU temperature: R^2 = 0.998; Hobo vs. EMU temperature: R^2 = 0.987, iButton vs. EMU humidity: R^2 = 0.986).

4.1 | Future engineering priorities

Environmental microcontroller units can potentially be expanded using their built-in WiFi. WiFi allows wireless "sensor networks" (Ingelrest et al., 2010) to measure microenvironment across larger spatial scales without human intervention. Data can be logged directly to the Internet, allowing remote monitoring of conditions in real time, or generating alerts.

Certain types of homemade radiation shields may bias temperature measurements upwards (Holden, Klene, Keefe, & Moisen, 2013; Terando, Youngsteadt, Meineke, & Prado, 2017). Although this limitation is not unique to EMUs, engineering better radiation shields that are cost-effective is a priority. Corrosion of untreated sensors and wire connections, over several weeks, increased failure rates during rain (Supporting Information Section 3.2). For all sensor types, moisture damage presents a problem, sometimes causing high failure rates (Anderson et al., 2015; Ashcroft & Gollan, 2013; Lebrija-Trejos et al., 2011; Lewkowicz, 2008). The failure rate in our study (11.4%) was comparable to those of commercial sensors. Subsequently, we have greatly reduced EMU sensor moisture failures by coating sensors with a silicone coating (Supporting Information Section 3.2).

5 | CONCLUSION

The easy-to-build EMUs we present provide an inexpensive and flexible alternative to commercial weather stations without sacrificing data accuracy. While DIY hardware and microcontrollers have been used occasionally in ecological research with great success, these methods have not yet captured the attention of the mainstream ecologist. Environmental microcontroller units can facilitate adoption of DIY electronics by a broader spectrum of scientists and students. The combination of flexibility, affordability, and accuracy opens new avenues for collecting the well replicated, high-quality fine-scale environmental data necessary to understand the responses of organisms to environmental gradients and rapid global change.

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AUTHORS' CONTRIBUTIONS

J.G.M. and T.E.M. designed, programmed, built, and tested the EMUs and analysed the data. C.D.S. and R.B. provided conceptual support. A.D. and E.N.P. helped build and field test units, and A.D. produced the video. All authors contributed to writing. The authors declare no conflicts of interest.

DATA ACCESSIBILITY

Data collected from our EMU field test and laboratory calibrations are archived from Github using Zenodo: https://doi.org/10.5281/zenodo.1663973, along with analyses, EMU code, and extensive documentation.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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