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Technical note

PARduino: a simple and inexpensive device for logging photosynthetically active radiation

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Photosynthetically active radiation (PAR, 400–700 nm) is one of the primary controls of forest carbon and water relations. In complex terrain, PAR has high spatial variability. Given the high cost of commercial datalogging equipment, spatially distributed measurements of PAR have been typically modeled using geographic coordinates and terrain indices. Here, we present a design for a low-cost, field-deployable device for measuring and recording PAR built around an Arduino microcontroller—named PARduino. PARduino provides for widely distributed sensor arrays and tests the feasibility of using open-source, hobbyist-grade electronics for collecting scientific data. PARduino components include a quantum sensor, an EME Systems signal converter/amplifier and an Arduino Pro Mini microcontroller. Additional components include a real-time clock, a microSD Flash memory card and a custom printed circuit board. The components were selected for ease of assembly. We found strong agreement between the PARduino datalogger system and National Institute of Standards and Technology traceable sensors logged by an industry standard datalogger (slope = 0.99, SE < 0.01, *P* < 0.01; intercept = −14.84, SE = 0.78, *P* < 0.01). The average difference between the two systems was 22.0 μmol m^{-2} s^{-1} with PARduino typically underestimating PAR. The average percentage difference between systems was 3.49%. On average, PARduino performed within the factory absolute calibration of the PAR sensor; however, larger errors occurred at low PAR levels. Using open-source technologies such as this can make it possible to develop a spatially distributed sensor network within the constraints of a typical research budget.

Keywords: Arduino, calibration, data acquisition, datalogger, open source.

Introduction

Photosynthetically active radiation (PAR, 400–700 nm) is one of the primary controls of forest carbon and water relations. In complex terrain, PAR has high spatial variability. Given the high cost of commercial datalogging equipment, spatially distributed measurements of PAR have been typically modeled using geographic coordinates and terrain indices (Dozier 1980, Dubayah 1994, Aguilar et al. 2010). With the introduction of open-source microcontrollers and software to the scientific research community, acquiring high spatial and temporal resolution environmental data is no longer cost prohibitive.

Many versions of open-source microcontrollers are available on the market today (e.g., Raspberry Pi, BeagleBone, Pinoccio, Texas Instrument's MSP430); however, Arduino microcontrollers are one of the more popular versions. Arduino is a group of open-source microcontrollers and software that is designed for physical computing (sensing and responding to the physical environment). The Arduino programming language is an implementation of Wiring, a similar physical computing platform, which is based on the Processing multimedia programming environment (www.arduino.cc). Arduino boards are relatively inexpensive compared with other microcontroller

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platforms with pre-assembled Arduino modules costing less than USD 50 in 2013. The Arduino software runs on Windows, Macintosh OSX and Linux operating systems and is published as open-source tools available for extension by experienced programmers. The language can be expanded through C++ libraries. The core platforms in the Arduino product line are based on Atmel's ATMEGA168 microcontrollers. The plans for the modules are published under a Creative Commons license, so experienced circuit designers can make their own version of the module.

Here, we present a low-cost, open-source device, named PARduino, for measuring and logging PAR using an Arduino microcontroller. This work represents our initial foray into the tools and techniques used by a burgeoning community of citizen scientists and electronic enthusiasts to conduct environmental monitoring (Gertz and DiJusto 2012). We were interested to see if these elements could be incorporated into a fundamental ecological research program. Our specific objectives were to (i) design and build an inexpensive microcontroller that is compatible with a research-grade PAR sensor and (ii) test our system against National Institute of Standards and Technology (NIST) traceable standard sensors to evaluate its accuracy and suitability for field deployment.

Materials and methods

Datalogger construction

PARduino was developed to be easy to assemble and program, be inexpensive and have low power requirements. The Arduino platform of hardware and software forms the backbone of the device because of the relatively simple programming language, widely available tutorials and its large support community. All PARduino components (Table 1) can be assembled by someone with a limited knowledge of electronics using off-the-shelf parts and through-hole soldering techniques (Figures 1 and 2).

Table 1. PARduino components and costs.

Item	Description	Cost (USD)
LI-190 SA	LI-COR Quantum (PAR) sensor	400
Arduino Pro Mini	3.3 V/8 MHz microcontroller	10
3.3 V FTDI basic	USB → serial converter for programming the Arduino	15
Deadon real-time clock	Drifts <1 min year^{-1}	20
microSD Flash socket	Holds the memory card	10
microSD Flash card	16 GB	10
Printed circuit board	Connects components	15
Amplifier	EME Systems UTA/BNC/190	150
6 V battery	8.2 A h	25
Miscellaneous parts	Wiring, connectors and enclosure	30
	PARduino total cost	USD 685

We selected the LI-COR quantum PAR sensor (Model LI-190SA, LI-COR, Inc., Lincoln, NE, USA) because these sensors have been used extensively in environmental research. Within the Arduino family of development boards, we selected the minimally designed, lower-cost Arduino Pro Mini (SparkFun Electronics, Boulder, CO, USA). The logic levels of the 3.3 V/8 MHz version of the Arduino Pro Mini interface directly with a microSD Flash memory card, and the Pro Mini's lower voltage, clock speed and lack of on-board USB-to-serial conversion circuitry reduce power consumption compared with other Arduino boards. Timekeeping is provided by a peripheral real-time clock consisting of an integrated circuit mounted onto a breakout board with a coin-cell backup battery and other passive circuit elements. The real-time clock is accurate to 2 ppm (drifts less than ~1 min year^{-1}) and has a programmable alarm used to wake the microcontroller. The real-time clock and the microSD Flash memory card both use the serial peripheral interface to communicate with the microcontroller. A printed circuit board was created to connect the Arduino, clock, memory card and screw terminals for the amplifier/PAR sensor input and for power. EME Systems' Universal Transconductance Amplifier (UTA) is a purpose-built unit to

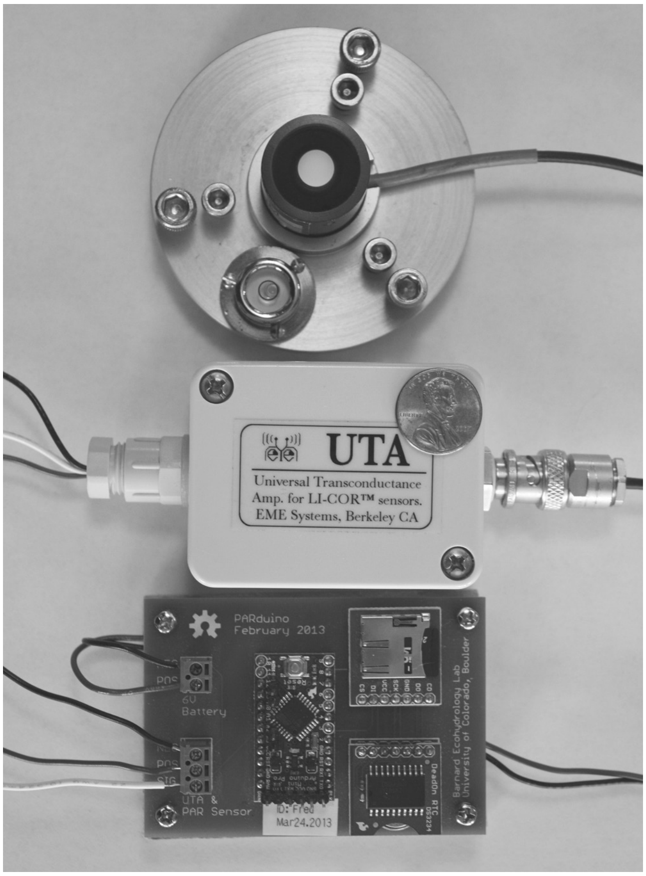

Figure 1. Photo of the assembled PARduino logger, EME Systems amplifier and LI-COR PAR sensor. A one cent coin (USD) is on the amplifier for scale.

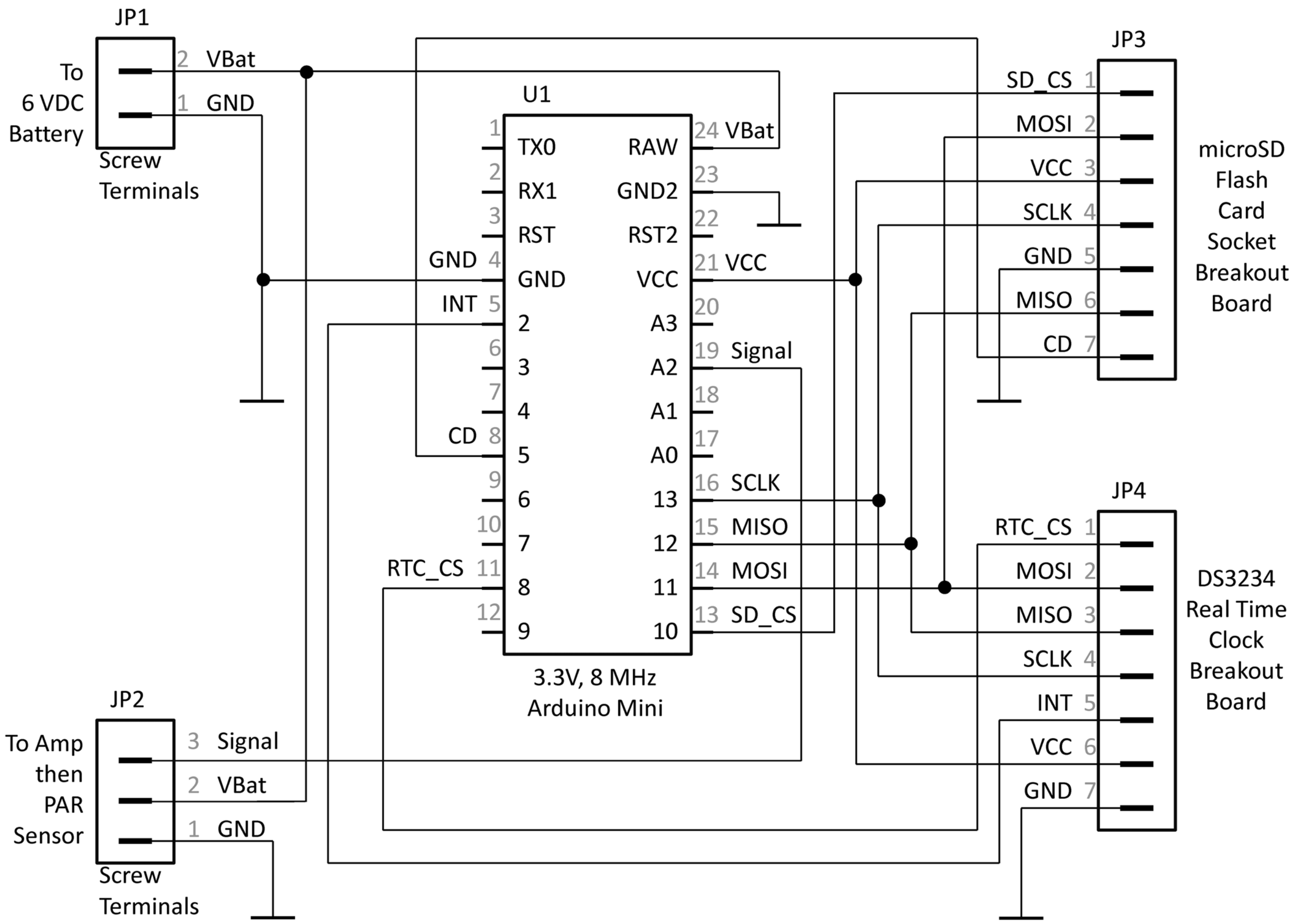

Figure 2. Wiring schematic of Arduino Pro Mini, breakout boards and other components. Gray numbers are pin numbers on the component boards. Pin names and wire labels use standard naming conventions described in Catsoulis (2005) and on component datasheets.

convert the signal from a LI-COR PAR sensor and amplify the signal to several different voltage ranges determined by setting switches on the amplifier. The amplifier has a gain accuracy of ±0.5% over all ranges at operating temperatures of −30 to 70 °C (EME Systems 2007). We set the amplifier's gain at 0.2 V µA^{-1} to match the 0–3.3 V range of the microcontroller's analog-to-digital converter. With this gain factor, PARduino has a resolution of ~2.3 µmol m^{-2} s^{-1} and a maximum value of 2366 µmol s^{-1} m^{-2}. Finally, PARduino is powered by a 6 V sealed lead-acid battery. This raw voltage is supplied to both the microcontroller and the amplifier (Arduino's voltage regulator supplies 3.3 V to the other peripherals). A 6-V battery was selected because the amplifier must be supplied with at least 5 V and the Arduino cannot accept DC input exceeding 12 V.

PARduino operates by acquiring data from the PAR sensor and recording the measurement on a microSD memory card. Photosynthetically active radiation detected by the sensor photodiode induces a small current (of the order of microamps) that has a linear relationship to photosynthetic photon flux density (µmol photons m^{-2} s^{-1}). The amplifier converts the current-based signal to a voltage output and amplifies the signal to between 0 and 3.3 V where it is read by the microcontroller's 10-bit analog-to-digital converter. Timing for data acquisition is controlled by the real-time clock that wakes the microcontroller from a low power state every minute. Provided a memory card is in the socket, the microcontroller acquires the single PAR measurement and date/time during each wake cycle and then writes the data to a file on the Flash memory card.

Field testing

The PARduino was deployed to the National Ecological Observatory Network (NEON) calibration radiation deck during October 2013 accompanied by eight PAR sensors (PQS1, Kipp and Zonen USA, Inc., Bohemia, NY, USA) calibrated to NIST traceable standards by NEON on 23 September 2013. Data for the PQS1 sensors were taken by a high-performance data-acquisition system (CR5000, Campbell Scientific, Logan, UT, USA) at a sample rate of 20 s. The LI-190 used for the PARduino system had a factory calibration dated 19 June 2012.

The PARduino sensor took an instantaneous measurement of PAR every minute. Measurements were recorded for a total of 10 days.

To compare the PARduino logging system with NEON-calibrated sensors, we performed a linear regression on the instantaneous measurements from the two systems and compared the results with the one-to-one line. Due to high spatial variability in PAR during cloudy or rainy periods, we parsed the full dataset to remove these periods, resulting in 4059 remaining clear-sky or near-clear-sky paired observations. Night-time values were also removed (values $< 100\ \mu mol\ m^{-2}\ s^{-1}$). To evaluate the relative error in PARduino measurements, we calculated the difference between the average NIST traceable PAR value ($n = 8$) and PARduino over the measured range of values.

Results and discussion

We found strong agreement between the PARduino datalogger system and NIST-calibrated sensors logged by an industry standard datalogger (slope = 0.99, SE < 0.01, $P < 0.01$; intercept = −14.84, SE = 0.78, $P < 0.01$) (Figure 3). The average difference between the two systems was $22.0\ \mu mol\ m^{-2}\ s^{-1}$ (standard deviation 23.44) with PARduino typically underestimating PAR (Figure 4a). This systematic offset could be due to calibration drift of the LI-190 sensor. The LI-190 sensor was factory calibrated over 1 year prior to this study. However, its only use had been in the design and development of PARduino; it had never been used for extended periods of time. The average percentage difference between the systems was 3.49% (standard deviation 3.88) (Figure 4b). On average, PARduino performed within the factory absolute calibration of the LI-COR PAR sensor (±5%); however, larger errors occurred at low PAR levels. This is likely a result of directional (cosine) response differences between the LI-190 and PQS1 sensors at high zenith angles (i.e., when the sun is low in the sky). When considering data recorded at zenith angles <70°, the average percentage difference between the two systems decreases to 2.49%. Additional factors influencing larger percentage differences at low PAR levels may include an offset in the time data that were recorded between the two systems (i.e., clocks were not precisely synced), PARduino's coarser resolution of $\sim 2.3\ \mu mol\ m^{-2}\ s^{-1}$ and larger relative errors at low values. These results indicate that given the resolution of the amplifier and PARduino datalogger, the system may not be appropriate for use when the comparison of low light levels is critical to research objectives. Despite these potential issues, the two systems closely tracked each other, albeit with offsets, during partly cloudy to cloudy conditions (Figure 5). Occasional large errors (up to 20%) were also observed at light levels $>800\ \mu mol\ m^{-2}\ s^{-1}$. Five percent of PAR values $>800\ \mu mol\ m^{-2}\ s^{-1}$ had an error >10%. We believe these errors are an artifact of the clocks not being precisely synced and other possible natural interferences in the comparison such as

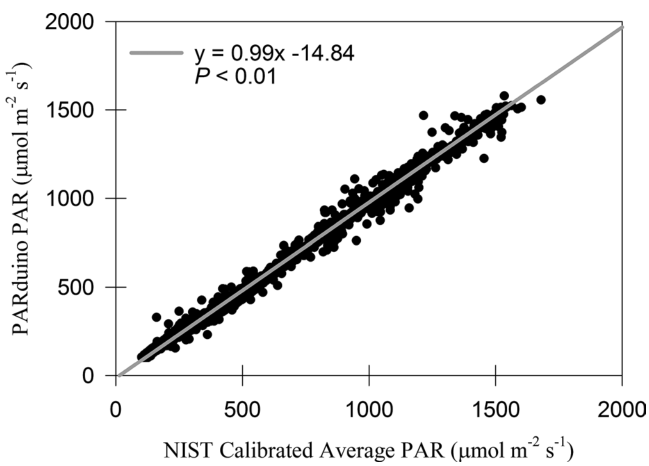

Figure 3. Photosynthetically active radiation measured by PARduino versus the average PAR measured by NIST traceable sensors ($N = 4059$). Night-time and non-clear-sky periods were removed from the original dataset.

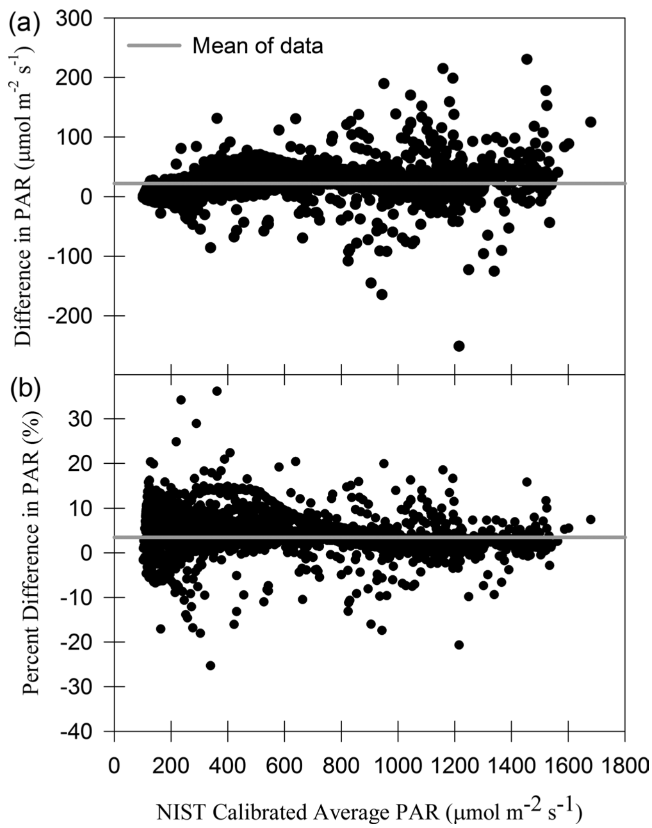

Figure 4. (a) Difference between average NIST traceable PAR and PARduino PAR versus the range of observed values. The gray line indicates the overall average difference for the dataset ($22.0\ \mu mol\ m^{-2}\ s^{-1}$). (b) Percentage difference between average NIST traceable PAR and PARduino PAR versus the range of observed values. The gray line indicates the overall average percentage difference for the dataset (3.49%).

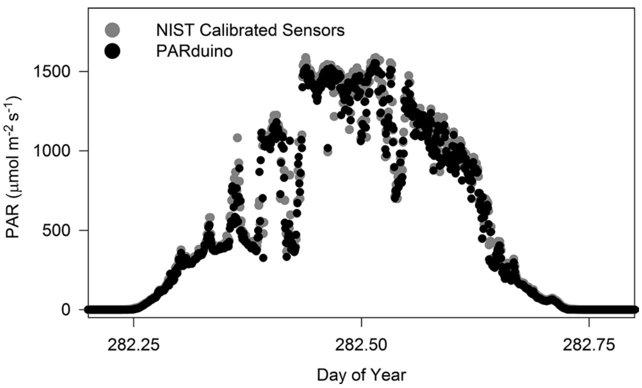

Figure 5. Time series of NIST traceable PAR and PARduino PAR values over 1 day with partly cloudy to cloudy conditions. Data were recorded at 1-min intervals.

small objects (e.g., birds, insects or personnel on site) temporarily blocking one or several of the sensors. When high light values are averaged over 15 min (a common measurement interval), the errors at high light decreased to 2.1% on average with a maximum of 7.7%. Although our dataset was limited to light values <1800 µmol m^{-2} s^{-1}, it was linear throughout the range, and we expect this linearity to persist at higher PAR levels.

The overarching goal of this project was to determine whether a hobbyist-grade microcontroller could be designed and used for research-grade field programs. This work was motivated by the need to reduce instrument costs. The PARduino datalogger is a reasonable alternative to higher-cost logging systems, but even greater cost savings can be realized through the design and construction of the other components of the light measurement system: the amplifier and the photodiode light sensor. Phillips and Bond (1999) presented the design and testing of a simple, precision current-to-voltage converter and amplifier. Their amplifier design has low power consumption and is suitable for field deployment. The current cost for their circuit components remains approximately USD 10. Designs also exist for low-cost photodiodes and diffusers for the measurement of light intensities (e.g., Fielder and Comeau 2000, Melbourne and Daniel 2003). With the introduction of three-dimensional printers, researchers can now design and print their own light sensors and enclosures for USD <10 (after purchasing a printer) (Brooks 2013, Ham 2013).

Given the additional opportunities for greater cost savings and enhancements to PARduino, we make this design publicly available as an open-source hardware device (OSHWA 2013). PARduino's design, including a bill of materials, circuit board layout files and source code, is available to everyone at an online source code repository (github.com/mfindley/PARduino) and is released under Creative Commons' Attribution-ShareAlike license. A portable document format file of the source code is also available as Supplementary Data at *Tree Physiology* online. We hope that it will be extended and improved by us and others. For example, PARduino's low-power sleep/wake/measure/store cycle can act as a framework for logging other environmental parameters beyond simply PAR.

This project demonstrates that all-purpose, prototyping electronic components (such as the Arduino) that are used by electronic enthusiasts for a broad range of applications can yield data of known and sufficient quality for fundamental ecological research. Although do-it-yourself datalogging projects like PARduino hold the promise of more widely distributed and richer datasets for a given equipment budget, any potential adopter should be prepared to invest a significant amount of time and effort into considerations that could otherwise be ignored. Debugging code and integrating basic electronic components such as sensors, amplifiers, analog-to-digital converters, microcontrollers and timers into complete measurement systems can take away from time devoted to the primary research objectives of a project. These types of devices may demand more scrutiny and verification than their corresponding commercially available data-acquisition platforms.

Conclusion

We designed and constructed a low-cost, open-source device for measuring PAR using an Arduino microcontroller. The microcontroller used with a commercially available voltage amplifier (together totaling about USD 285, not including the PAR sensor) provides a viable alternative to commercial, research-grade dataloggers. Additional cost savings could be gained by constructing the signal amplifier in the laboratory rather than purchasing one commercially. Three-dimensional printers are providing the opportunity for researchers to build their own PAR sensors further reducing the cost of radiation measurements. Using these open-source technologies can make it possible to develop a spatially distributed network for less than USD 200 per sensor, amplifier and datalogger combined.

Supplementary data

Supplementary data are available at *Tree Physiology* online.

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Conflict of interest

None declared.

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