Fluxbot: The Next Generation - Design and Validation of a Wireless, Open-Source Mechatronic CO_2 Flux Sensing Chamber

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ABSTRACT

Precision gas analyzers are widely used in ecological research for manual measurement of soil carbon flux, a key metric used in the study of climate change. We present a generational update to the first low-cost, autonomous, closed-chamber style soil CO_2 flux sensors (Fluxbots). Fluxbot 2.0 is the first such low-cost autonomous flux chamber capable of real-time wireless data transmission, which enables ecologists conducting *in situ* soil carbon flux surveys to set up their own wireless sensor arrays, reporting carbon flux data in real time at a very high level of temporal resolution. The system's low cost (less than 500 USD per unit) and long-range cellular data transmission capabilities also allow for greatly improved spatial resolution. Additionally, the updated system consumes significantly less power, resulting in the ability to be deployed for longer than 10× the battery lifetime of the original version on a single charge.

CCS CONCEPTS

• **Applied computing** → **Environmental sciences**; • **Human-centered computing** → *Ubiquitous and mobile computing systems and tools*; • **Computer systems organization** → **Sensor networks**.

KEYWORDS

Wireless environmental sensing, ecology, open-source

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1 INTRODUCTION

Soil carbon flux (the rate of CO_2 exchange between soil and the atmosphere) is a metric widely used by ecologists to construct detailed models of how carbon cycles through an ecosystem. In addition to improved ecosystem carbon models, monitoring a system's soil carbon flux at a high resolution could be useful in supporting strategies to reduce soil carbon emissions for climate mitigation [15]. High-resolution, low-cost soil carbon flux monitoring could, for example, support a data-driven approach for carbon tax credit programs, as opposed to the current estimate-driven approach (which has been criticized due to its allowance of systemic over-crediting, as shown in [6]).

Greenhouse gas fluxes are dynamic through space and time (e.g., different ecological and management contexts [22]). Constructing a greenhouse gas budget for a given site or management application thus requires temporally-intensive measurements across diurnal, seasonal, and/or climatological conditions, and extensive measurements at a landscape scale. Existing soil carbon flux measurement methods frequently consist of chambers placed on the soil's surface, that use internal CO_2 detection mechanisms to monitor the rate at which CO_2 is emitted from the soil to the chamber's internal volume. These chamber-based tools offer high precision and reliability (fig. 2). However, manual collection of these data means such tools cannot provide the option to collect soil carbon flux data *simultaneously* at both high and broad spatial and temporal scales. This inability limits researchers' and managers' capacity to collect appropriate data for addressing certain types of ecological questions or management targets [11], [24].

There are therefore key advantages to using *automated* chambers to monitor soil carbon flux [27] [23], or chambers that autonomously close for a predetermined interval during which they

Figure 1: A Fluxbot 2.0 installed *in situ*

monitor the buildup of CO_2 internally, before autonomously opening to vent. A major advantage of *low-cost*, independently-operating, and autonomous chambers, specifically, is that researchers can deploy many individual chambers in the field, enabling detection of soil carbon flux at higher spatial resolution and at larger spatial scales than is possible with commercially-available automated chamber systems [11]. (See Forbes et al. (2023), wherein the authors designed and tested the novel, inexpensive and open-access "Fluxbot", an autonomous soil carbon flux chamber. They demonstrated, in a proof-of-concept two-month field deployment in a central Kenyan savanna, that a distributed array of Fluxbots collected an unprecedentedly high-resolution dataset that captured previously-unknown characteristics of the ecosystem's soil carbon dynamics [11].)

Critically, the addition of *wireless* capabilities would allow for better deployment and real-time monitoring of an even more widely-distributed array of Fluxbots, for example across far-flung study sites [21]. A key advantage of wireless sensing is that devices are installed at their deployment sites once, with an operational lifetime of however long their batteries last. Wireless-capable Fluxbots would greatly reduce the amount of in-person data collection (i.e. downloading from memory cards) required to monitor soil carbon flux across what can be complex, environmentally hostile, or difficult to access landscapes. While initial attempts at implementing autonomous soil carbon flux chambers capable of remote data transmission have been promising [7, 25, 26], to adhere to our goals of low-cost, high-resolution soil carbon flux monitoring (as enumerated by [Forbes et al]), it is essential that adding wireless capability not increase the instrument's cost. It is also essential that a wirelessly-capable Fluxbot design is accessible to those who would use it: ecologists, Earth scientists, agriculturists, and other practitioners of ecosystem carbon data collection. In other words, there is a need for a low-cost, open-source wireless sensing platform that does not require extensive technical expertise to deploy.

Here we present an improved and accessible generational update to the existing Fluxbot system (the first truly open-source and autonomous soil carbon flux chamber operating at extremely high resolution and extremely low cost [11]). Critically, this update (Fluxbot 2.0, hereafter referred to as "Fluxbot" for simplicity) introduces wireless data transmission capabilities, allowing for remote data collection and monitoring and therefore making the Fluxbot even easier to use across large spatial extents and in remote locations. The Fluxbot now not only stores, but transmits hourly soil carbon flux data to an online data repository (Google sheets) in real time. This capability allows researchers to remotely monitor individual *and* Fluxbot array performance, a task which previously required the time-consuming step of travel to, and collection of data from, each Fluxbot in a distributed array. As such, the Fluxbot's remote data transmission functionally expands the potential spatial footprint of an array's distribution across a landscape.

In this update, we prioritized reproducibility and ease of use. We switched from a custom-fabricated PVC chamber to a commercially available alternative, switched out the original CO_2 sensor choice for a better-studied and highly verified option, and implemented a hinge-mounted rotational servo to actuate the chamber lid (rather than a linear actuator). To improve the system's ease of use, we implemented wireless data transmission via a cellular network (allowing individual Fluxbots in an array to collect and transmit data so long as there is at least low-quality cellular service in the area). We improved battery life from an estimated 24 hours (Fluxbot 1.0) to approximately 317 hours on average (Fluxbot 2.0), a 1220% increase in operational lifetime over the original version. This large improvement in operational lifetime comes without the use of solar panels to recharge the battery, allowing us to deploy the updated Fluxbot in low-sun areas (e.g., higher latitudes, under forest canopy).

In Section II, we discuss current approaches to soil carbon flux sensing and related soil and climate science wireless sensor network implementations. In Section III we discuss Fluxbot system design, hardware and software, and physical assembly of the device. In Section IV we cover sensor and system validation tests, including testing several iterations of prototypes. In Section V we discuss results from field tests, and future improvements to the design; in Section VI we draw conclusions from these tests and anticipate future improvements to the Fluxbot design.

2 RELATED WORK

There are a variety of chamber-based, even autonomously-operating commercial soil carbon flux devices currently available (table 1). These modern chambers utilize high-precision sensors like infra-red

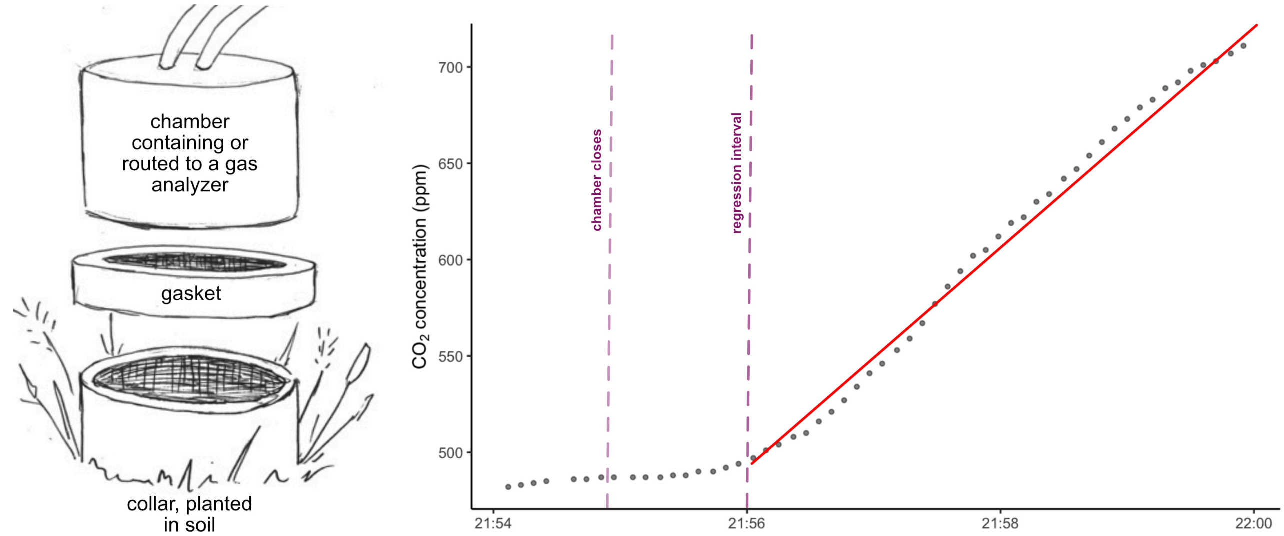

Figure 2: The physics of chamber-based soil flux measurements include placing a chamber on the soil surface, generally on top of a pre-installed "collar" (that once installed, by pressing it into the soil by several centimeters, prevents further disturbance to soil biology while collecting data), and a gasket to create an air-tight volume. By monitoring the increase in internal chamber CO_2 concentration over the course of several minutes, researchers can take a regression of these data and (using ideal gas laws to convert concentration to mass, and the chamber's volume and area) calculate an estimate of CO_2 efflux. (Right-hand image an example of real concentration data collected with a Fluxbot, with lines demonstrating chamber closure and regression start.)

Table 1: Current Automated Flux Measurement Solutions

	Fluxbot 1.0	**Fluxbot 2.0**	**PP Systems[1]**	**LI-COR[2]**	**Eosense and Gasmet[3]**	**Eosense and Picarro[4]**
Method (static or dynamic)	static	static	dynamic	dynamic	dynamic	dynamic
Single or Multiplexed	single	single	single	multiplexed	multiplexed	multiplexed
Gas detection method	NDIR	NDIR	IRGA	IRGA	FTIR	CRDS
Wireless communication	N/A	LTE	Wi-Fi	LTE	Wi-Fi	Wi-Fi
Power Supply	DC Battery (24 hours)	DC Battery (317 hours)	AC Source	AC Source	AC Source	AC Source
Estimated price[5] (n=1) (USD)	362	379	9,975	15,175	69,804	114,335
Estimated price (n=5) (USD)	1,810	1,895	49,875	65,425	102,109	146,640

1. PP Systems CFlux-1 Automated Soil CO_2 Flux System
2. LI-COR 870 gas analyzer + 8250 multiplexer + 8200-104 long term auto chamber
3. Eosense eosAC-T/O Automated Soil Flux Chamber + eosMX Multiplexer + Gasmet GT5000 Terra Gas Analyzer
4. As above, but with a Picarro G2311-f Dual-Mode Greenhouse Gas Analyzer instead of the Gasmet analyzer
5. Multiplexer not included in cost estimate (not required for n=1)

gas analyzers (IRGA), cavity ring-down spectrometers (CRDS), or Fourier transform infrared spectrometers (FTIR) to detect real-time changes in CO_2 inside a closed volume over time. "Survey" systems consist of a chamber connected to a sensor via a flow-through pump system, which is then placed over the soil to create a closed-system volume within which CO_2 accumulation can be monitored [14] (fig. 2). Other designs rely on a chamber that estimates flux rate by measuring the concentration of CO_2 as it enters the chamber through a valve of known aperture, and again as it leaves [20]. Variation in chamber design, sensing mechanism, and state (e.g. static vs. dynamic) can lead to significant differences in flux detection, but are generally consistent in detecting relative patterns in flux (in time, across space, etc.) (e.g. [13] and [9]).

Newer, autonomously-closing chambers that do not require a user to operate them are increasingly available commercially. Table 1 includes both generations of Fluxbot, as well as a subset of several commonly-used commercial options for automated flux sensing. (For the sake of the most direct possible comparison, we omitted the many handheld survey chambers available commercially from this limited subset. However it should be noted that even our comparison across autonomous systems is not exact, given differences in mechanics and deployment strategy between designs.) Earth science and ecosystems scientists have also published high-resolution data from homemade autonomous chamber systems (e.g. [23], [22]). The vast majority of autonomous systems (both commercial and homemade) are multiplexed, or an array of autonomous chambers connected to a central sensor node via information and gas exchange pathways (inlet and outlet tubes) such that a single chamber is triggered to close at a time for a flux observation interval. While high resolution in both space and time, the spatial distribution of such multiplexed systems can be limiting depending on terrain, ecosystem complexity, wildlife, and other environmental variables due to the need for connecting wires and tubes. Likewise, many commercial options require AC power to operate, restricting potential deployment area and increasing cost.

Current approaches to soil carbon flux monitoring can be prohibitively expensive specifically when increasing temporal and spatial resolution of data collection, in addition to areal extent. Survey chambers (including detector and chamber) can cost tens of thousands (USD) per system, require an operator, and produce one flux measurement at a time per location, constraints which can result in low data resolution depending on the extent of a monitoring team's research location. Though autonomous systems allow for higher temporal resolution, they can cost additional tens of thousands of dollars (USD). While incredibly important tools whose high precision makes them invaluable to ecosystems research, these realities highlight a gap in the market for projects seeking to expand data collection capacity in spatial and temporal resolution in addition to scale.

2.1 Benefits of Remote Monitoring for Sustainability Applications

The addition of wireless data transmission capabilities to the Fluxbot design not only improve its applications for basic research, but also for sustainability. Remote monitoring has revolutionized practices in sustainability research, like long-term monitoring of the state of and changes to habitats' structural characteristics, wildlife or plant communities, and local-scale climate patterns [5]. For soil carbon in particular, remote monitoring allows researchers to (for example) identify patterns in soil carbon: where it is likely most abundant, where it is possibly most vulnerable, where land use change is prompting change, and more [16]. Real time remote monitoring can also allow for swift decision making in response to conditions that require remediation, for example short-and long-term application of soil amendments to promote atmospheric CO_2 sequestration [10]. Critically, remote monitoring can also contribute to lowering the substantial costs of entry to monitoring soil carbon dynamics [19], making larger-scale exploration [4] and monitoring in understudied locations [11] more feasible.

To wit, we postulated that the addition of remote monitoring capability to the Fluxbot would greatly improve the application space for which the Fluxbot can be useful. For example, the ability to monitor a Fluxbot array's data in real time via remote data transmission would allow for researchers to deploy a much larger and/or widely distributed array, as data collection occurs passively. Such capability would also improve the resilience of an array, as malfunctioning Fluxbots can be detected remotely "live", enabling swift repair or replacement and returning an array to full statistical power quickly.

3 SYSTEM DESIGN

3.1 Technical Requirements

There are a number of technical requirements for a system capable of monitoring soil carbon flux. First, the interior of the chamber must be airtight when closed and measuring, to create a consistent volume inside which to accurately detect CO_2 accumulation [8]. However, in order to allow for ambient gas exchange when not in a measurement interval state, the lid of the chamber must be actuated to open on a predetermined schedule. The system must also be resilient to adverse weather conditions such as heavy rainfall. Finally, to reduce the amount of necessary *in situ* visits (e.g. troubleshooting, battery replacement) as much as possible, the battery life of a single unit must be considerable. We aimed for an operational lifetime of at least ten days.

3.2 Mechatronics

3.2.1 *Gen2 Fluxbot Components and Design.*

To simplify assembly for replication (and keep cost per unit down), we prioritized using low-cost, off-the-shelf components for the Fluxbot system. Instead of machining our own hinged chambers[11] (which requires extensive preparation and air-tightness testing), we purchased commercially-available PVC sewer caps with hinged lids originally designed for use with RV septic systems (fig. 3). The product is made with chemical and temperature resistant materials, and is airtight when closed. A useful feature is that the sewer cap has male threading at the bottom, and can directly screw into corresponding 4" SCH 40 PVC couplers. These couplers (hereafter "collars") can be installed (i.e. placed flush to the soil's surface female threaded side up, pressed approximately 4cm deep) at Fluxbot deployment sites, and a Fluxbot chamber screwed in place. (This design decision allows us to move a single fluxbot between sampling collars, without disturbing the soil underneath.)

The sewer cap has a strong torsion spring at the hinge of the lid, forcing the chamber closed if no force is applied on the back lever; we cut the legs of the spring so that it can be opened with significantly lower force, and power. This decision allowed us to conserve battery power, as the Fluxbot chamber remains open for the majority of the time between short closures for flux measurement intervals.

We designed a custom, 3D-printable electronics bracket to house the Fluxbot's sensing electronics (CO_2, relative humidity and temperature, and pressure sensors) and attached it to the underside of the lid using hot glue (fig. 3). The bracket is small enough to fit within the internal diameter of the sewer cap without interfering with chamber closure. We routed each sensors' cables (1m jumper wires) from their locations on the bracket through a hole drilled in the lid, sealed with an airtight cable gland and silicone to prevent air leakage from the chamber in its closed state.

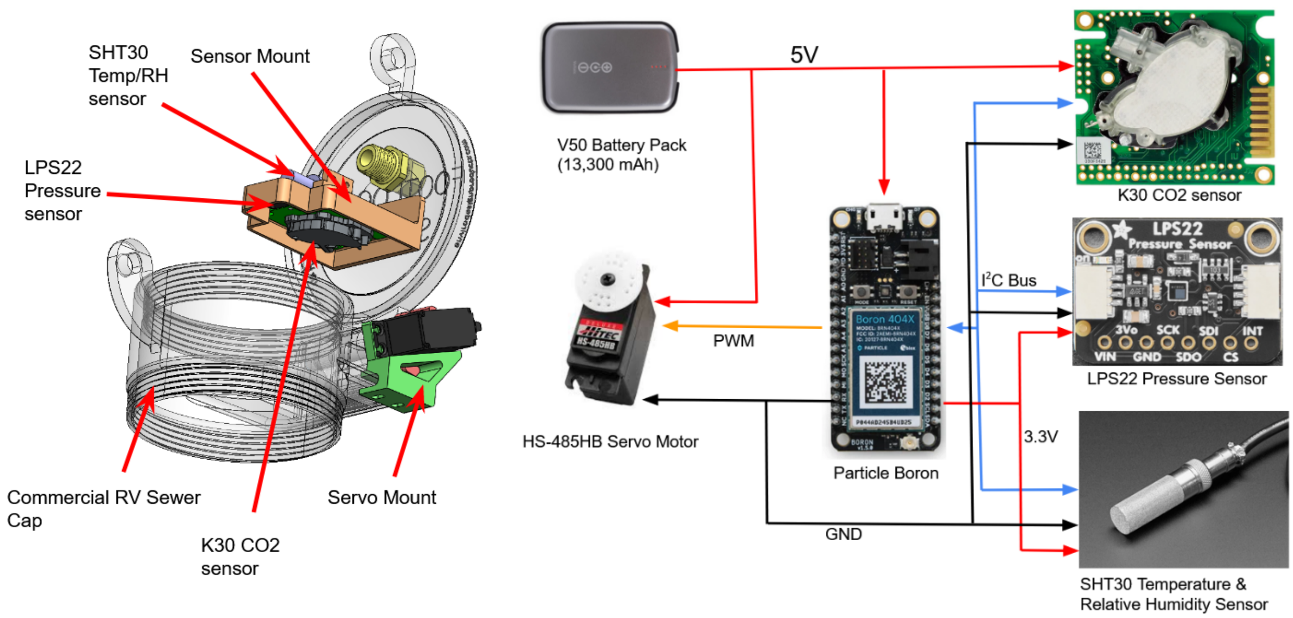

Figure 3: (left) CAD model of a Fluxbot unit; (right) system block diagram for Fluxbot hardware components.

3.2.2 Actuation Hardware. We designed a custom, 3D-printable servo motor mounting piece which attaches to the outside of the chamber lid, such that the servo motor's rotation axis aligns with the hinge axis of the lid. We designed a second piece which attaches the servo horn to the chamber lid itself, opening and closing the lid as the servo motor rotates. (The bracket, servo mount, and lever interface pieces were all 3D printed with a Nylon polymer in a multi jet fusion process.)

To actuate the chamber lid at desired times, we chose a servo motor with sufficient torque to rotate the hinge lid at the voltage provided from an always-on, rechargeable battery pack (fig. 3). Given the weight of the lid and the electronics mounted to it, we selected the Hitec HS-485HB servo which provides more than sufficient torque (up to 0.5Nm) at 5V and is quite inexpensive ($20). (The actuation hardware was designed to be easily removeable with a Philips head screwdriver in the field if a servo needs to be replaced; additionally, if different or additional sensors are added to the Fluxbot, adding weight, the HS series servos are almost identical in dimensions and could be swapped into the mounts with little to no modification.) As an added measure to improve reliability when deployed in the field, we coated the seams of the servo's plastic enclosure with liquid electrical tape to prevent moisture ingress.

3.3 Electronics

3.3.1 Microcontroller. In keeping with the objective of accessibility, we chose a commercial microcontroller unit instead of using a system-on-a-chip (SoC). We used the Particle Boron, based on the Nordic nRF52840 SoC with an onboard uBlox LTE modem for wireless communication. The Boron is inexpensive, computationally powerful, and does not require external peripherals for wireless data transmission. Particle has published extensive documentation on every aspect of the Boron, from low-level hardware to every command in the device API, allowing users to effectively troubleshoot without requiring extensive prior experience with embedded systems development. Furthermore, the online Particle Forums are managed by Particle engineers, offering a robust yet welcoming community to assist in troubleshooting problems that arise.

3.3.2 Sensors. For CO_2 detection, we selected the Senseair K30 due to the abundance of available literature supporting its accuracy and precision in relation to more expensive CO_2 sensors [17, 18]. The K30 is a nondispersive infrared (NDIR) gas analyzer, which measures CO_2 concentration in parts per million (ppm) by detecting the net absorption of an infrared (IR) light beam by CO_2 in the beam's optical path. As NDIR gas sensors are optical sensors, they are more precise than other CO_2 sensing methods such as metal oxide-based approaches [3]; however NDIR sensors are susceptible to the interacting effect of moisture, particularly at high relative humidity levels, requiring physical protection of the sensor from water and the simultaneous detection of relative humidity to correct for air moisture content when converting CO_2 concentration to units of mass. To monitor relative humidity (and other important atmospheric metrics necessary for the conversion of CO_2 concentration to mass) we selected the shielded (aka waterproof) Sensiron SHT-30 temperature and relative humidity sensor and the LPS22 barometric pressure sensor from STMicroelectronics. These hobbyist sensors' cost, ease of use, extensive online documentation, and wide availability make them attractive choices for a low-cost soil carbon flux system.

3.3.3 Power. To power the device, we selected Voltaic Systems' V50 outdoor battery pack, which has a max capacity of 13,300 mAh, due to its robust build and "always on" feature (allowing for low

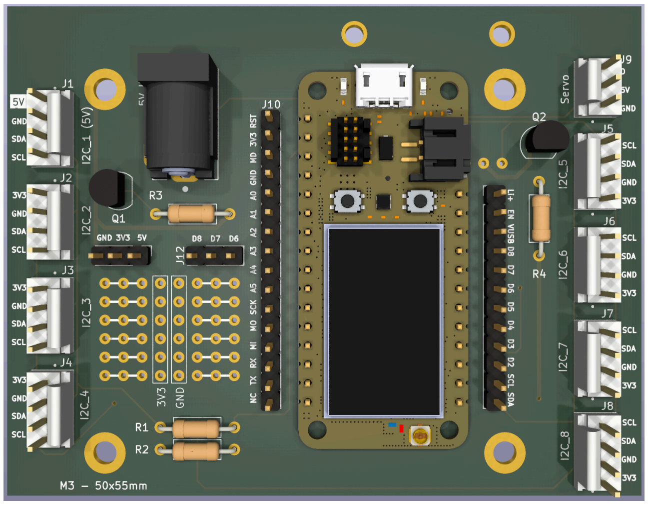

Figure 4: Render of Fluxbot PCB

power draw without shutting off, thus maintaining functionality while the Fluxbot is between observation intervals). We measured the power consumption of the system using a desktop power supply, and calculated the maximum battery life for the system (using a weighted average to approximate average hourly current draw at 40.339 mA) at approximately 329.7 hours of continuous operation, or just over 13 days in the field. This time period is roughly equivalent to 329 measurement intervals (one per hour) per Fluxbot, a massive improvement in temporal resolution over manual sampling methods.

3.3.4 PCB Design. We designed a custom printed circuit board (PCB) to facilitate scaleable, reproducible construction of the Fluxbot electronics (fig. 4). The primary design goals were to be cost-effective and easy to assemble (contrary to the original Fluxbot design, which was hand-wired and thus more difficult to replicate effectively at high numbers).

The PCB can support up to eight sensors via a standard 4-pin connector with I^2C and power. This modular approach allows the PCB to communicate with a wide variety of commercially-available environmental sensors, while leaving room for replacements (e.g., a different make or model of CO_2 sensor) and additions (e.g., the inclusion of sensors for other greenhouse gases like methane). One of these ports is dedicated for sensors with high current draw (such as the K30 and other NDIR CO_2 sensors), using a separate 5V power rail which can be toggled on or off using a MOSFET connected to a digital GPIO pin. This setup allows the system to cut power to high-current peripherals to conserve battery life during the Fluxbot's deep sleep mode (fig. 5). We included a similar 3-pin port to control the chamber lid servo, which can also be toggled via GPIO to conserve power. The top of the board contains a barrel jack input for the 5V high current system. The rest of the system is powered by the 3.3V regulator onboard the Boron, which in turn gets its power via micro-USB connection to the battery pack. Additional features on the PCB include a microSD card reader connected via SPI (as a data collection backup if cell coverage cannot be reached), and a breadboard-like prototyping area for future expansion.

The PCB has a condensed layout and is implemented in two layers to minimize cost. We used widely available thru-hole components (e.g. Boron headers) for quick and easy assembly. This project uses MTA connectors for easy crimping and durability in the field, but the footprints support any standard 0.01" header to make the design more accessible to those who wish to reproduce the project.

3.3.5 Weatherproofing. To ensure that the battery and PCB are not exposed to the elements, we used a commercially available weatherproof electronics box to house the battery, microcontroller, and PCB. To maintain the watertight enclosure of the electronics box while also connecting sensor cables from the Fluxbot chamber to the PCB, we routed cables through a cable gland installed on a hole drilled into the side of the box. We used an identical cable gland on a second hole to route an antenna from the outside of the box to the Boron inside. (To protect the exposed sections of the cables, we used a length of standard mesh protective sleeve.)

3.4 Software

We designed the Fluxbot's software architecture to be understandable and straightforward. We created a finite state machine that changes state based on system time (for each Boron microcontroller, time is synced to the Particle Device Cloud via LTE network upon activation). We chose LTE for its ease of use and low cost, as Particle charges for cellular service based on number of data operations/API calls (350 USD per month per 750k data operations). In addition, we chose to avoid protocols that require inter-unit networking (such as LoRA) for array resilience: as a connected but un-networked array, when a single unit malfunctions the operations of the rest of the array are not compromised. The software cycles through five distinct states each hour (fig. 5). Because we used commercially-available sensors, we were able to take advantage of their open-source software libraries, greatly reducing the technical expertise required to deploy an array of Fluxbots; device libraries may simply be imported to the Boron through an integrated development environment (IDE) such as Visual Studio Code or the Arduino IDE, instead of requiring users to write custom device drivers. Using off-the-shelf sensors therefore improves the overall accessibility and customizability of the system for researchers without extensive electrical engineering experience.

During data collection, the Fluxbot reads from each connected sensor over a shared I^2C bus at a frequency of 0.16 (1/6) Hz. This sampling speed was largely chosen to accommodate the sampling rate of the K30, which can sample once every two seconds. All sensors' data are stored locally until 20 measurements have been completed (equivalent to two minutes of active measurement); at this point, the Boron packages the data into four JSON files and uploads them to the cloud via LTE, clearing the buffer for the next two-minute package of measurements. As each measurement interval consists of six total minutes of measurement, this process is repeated three times per interval. (The first minute of each measurement interval occurs while the Fluxbot chamber is open to record ambient atmospheric conditions, after which the chamber lid closes and the remaining five minutes consists of measurements of the closed Fluxbot's internal chamber volume.) Once the six-minute

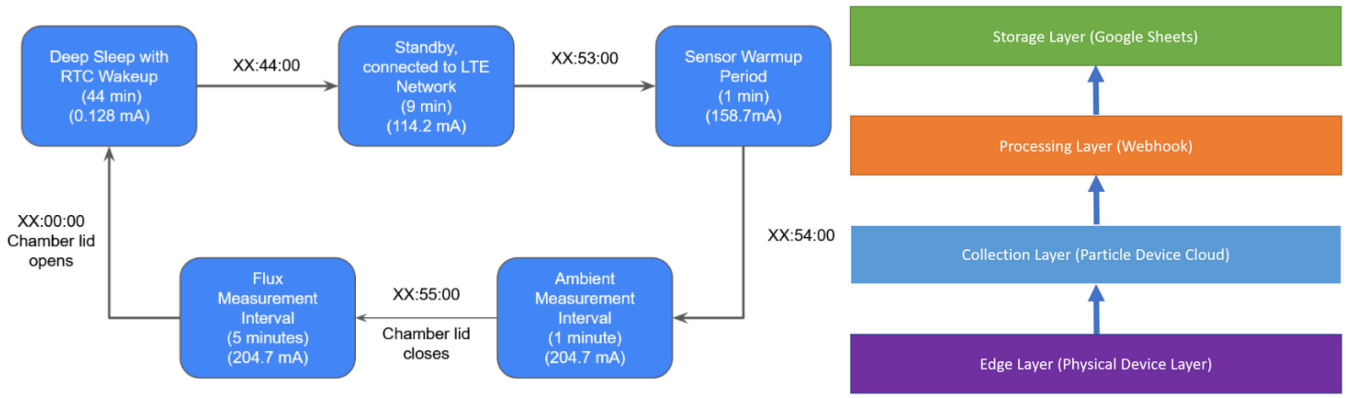

Figure 5: (left) State transition diagram of Fluxbot algorithm, (right) Fluxbot software stack

measurement interval is completed, the number of anomalous measurements (compared to user-defined parameters for acceptable ranges of sensor values) and the number of error codes is calculated, and the number of errors is compared to a user-defined threshold. If the amount of errors exceeds this threshold (which can occur due to environmental anomalies like wildlife interference, condensation on the sensors' surface, etc.), then the system will reset itself, causing the sensors to re-initialize and recalibrate. This functionality helps users quickly identify units that are malfunctioning by observing the number of system resets on the incoming data stream, and enables some measure of self-correction during an outdoor field deployment.

By using the Particle Device Cloud's proprietary device cloud service for remote data transmission, we were able to further reduce the technical complexity of deploying a Fluxbot array. Instead of writing a custom transmission protocol we were able to package the sensor data into a JSON file onboard the Boron, upload the data to the Particle Device Cloud over LTE, and pull it from the cloud via a standard webhook. A custom Google Apps Script stores data from the webhook in a shared Google Sheet, separated by timestamp and device identifier. While not standard practice for storing IoT device data, this Google Sheets approach allows users to quickly set up their own data storage scheme without extensive programming experience or setting up their own cloud server architecture.

3.5 Data Processing & Flux Estimate Production

To produce soil carbon flux estimates from raw CO_2 concentration data for each observation interval, we closely followed the strategy from Forbes et al. [11]. In short, the K30 sensor reports CO_2 concentration in parts per million. We converted each observation to mass density of CO_2 using ideal gas laws, chamber volume, and atmospheric pressure (collected contemporaneously from nearby meteorological stations and verified with data from the on-board LPS22 sensor), temperature, and relative humidity (data from the SHT30 mesh-protected sensor) (see Table 1 in Forbes et al. [11]) (thus accounting for water vapor in the air inside the chamber, an especially important consideration given that test deployments were all conducted in New England in autumn).

After this conversion we conducted linear regressions on the last four minutes of data for each interval (removing the first minute of data during Fluxbot chamber closure to account for the time it took for the lid to close, and the internal conditions to stabilize). Using the β_1 value for each regression (i.e., slopes describing the increase in CO_2 in mass units of CO_2 per second), we estimated flux by dividing by the area of soil contained by the fluxbot's PVC collar. (We report linearly-derived flux estimates here, though we also calculated flux estimates with a second-order polynomial, or quadratic, regression; the two estimates are closely aligned in the vast majority of cases except for outliers. Determining best practice for calculating regressions to estimate flux is an ecological challenge beyond the scope of this paper[11][22]; for the sake of simplicity we report linearly-derived estimates.) We again followed the mathematical procedure in Forbes et al. 2023[11], including rigorous quality control that automatically removes any observation intervals with possibly-erroneous data.

To generate flux estimates for the entire array, we wrote a custom R function that iteratively conducts the above mathematical conversion of CO_2 concentration to mass density, and estimates flux using linear regression for each observation interval in a time series.

4 EVALUATION

Prior to full-protoype testing (e.g., installed in the soil surface), we calculated an estimate for system battery life using a desktop power supply (approximately 329 hours, or 13.7 days, on a single fully-charged battery pack). We validated this estimate by running several full electronics systems on charged battery packs in the lab. (This estimate is the upper end of the average functional life of the Fluxbot system in the field, as battery pack longevity is negatively impacted by both hot and cold ambient conditions; therefore, we did not test real-world battery life estimates until the outdoor testing stages (see below).)

In addition to calculating battery life, we streamlined the assembly process to allow for scaling production of Fluxbots for mass deployment operations. This included several rounds of experimentation to determine the best process for efficient, accurate assembly of an array of fluxbots. Ultimately, we determined that the most efficient process includes pre-assembling an array's fluxbot lids first, by hot-gluing the sensor mount in place and installing the requisite sensors on the sensor mount, wrapping the exposed jumper wires in PET braided wire sleeving, and threading the wrapped wires through the cable gland installed in the hole in the fluxbot lid. We sealed the internal opening to the cable gland with silicone to ensure an entirely airtight volume when closed and left the completed lids to dry for 24 hours. For each Fluxbot, we assembled a "Fluxbot kit" containing the electronics box's contents, and stored it with its associated, assembled lid. This setup allowed for fast assembly of a lid to its electronics unit immediately prior to, or even in the field.

4.1 System Stress Testing

We tested a Fluxbot prototype in a variety of high-humidity outdoor environments across New England to explore possible stressors to the system. These tests demonstrated that, at very high (99%+) relative humidity (e.g. during and post-rainfall), some K30 sensors reported unrealistically high CO_2 concentrations (e.g. a significantly positive offset from the possible range of 'true' ambient CO_2). We posit that under extremely high relative humidity, and because the K30 is an NDIR sensor, it becomes possible for condensation to form on the K30 sensor's surface, creating a sort of naturally-derived visual filter that produces these spuriously high CO_2 concentrations by absorbing additional visible light in the optical path. We addressed this by wrapping the K30 in a thin envelope made out of polytetrafluoroethylene (PTFE), creating a gas-permeable and hydrophobic layer to prevent liquid water from condensing on the sensor's surface. Through continued testing, we determined that while the PTFE envelope does not prevent liquid water buildup on the K30's optical surface in all cases (e.g. during extremely heavy rainfall events), it delays the onset of spuriously high CO_2 concentration values (and critically, also prevents a sensor-damaging amount of moisture buildup that would result in sensor failure).

Through these stress-tests we also determined that the fully-assembled prototypes were unable to sustain a successful actuation from the closed to open position, due to the high power needs of the original servo motor we selected. As the battery packs began to lose charge, the Fluxbots eventually became stuck in the closed position far earlier than their estimated battery life had suggested. We upgraded the servo motor to a stronger model (identified above; Hitec HS-485HB) which ensured continued actuation for the duration of a charged battery's *in situ* lifespan.

After these improvements, we conducted two test deployments: first, a single Fluxbot deployed locally in two controlled environments at Yale University, comparing Fluxbot performance directly to a high-precision commercial gas analyzer; and second, a deployment of 16 Fluxbots in a long-term ecological research site in a rural Massachusetts temperate forest to assess data transmission and overall system performance.

4.2 Outdoor and Laboratory Mesocosm Testing

We created a testing apparatus to compare Fluxbot performance to that of a high-precision, commercially-available (and widely used) CO_2 analyzer (Los Gatos Research Microportable Greenhouse Gas Analyzer, M-GGA-918; henceforth "LGR"). We attached the LGR

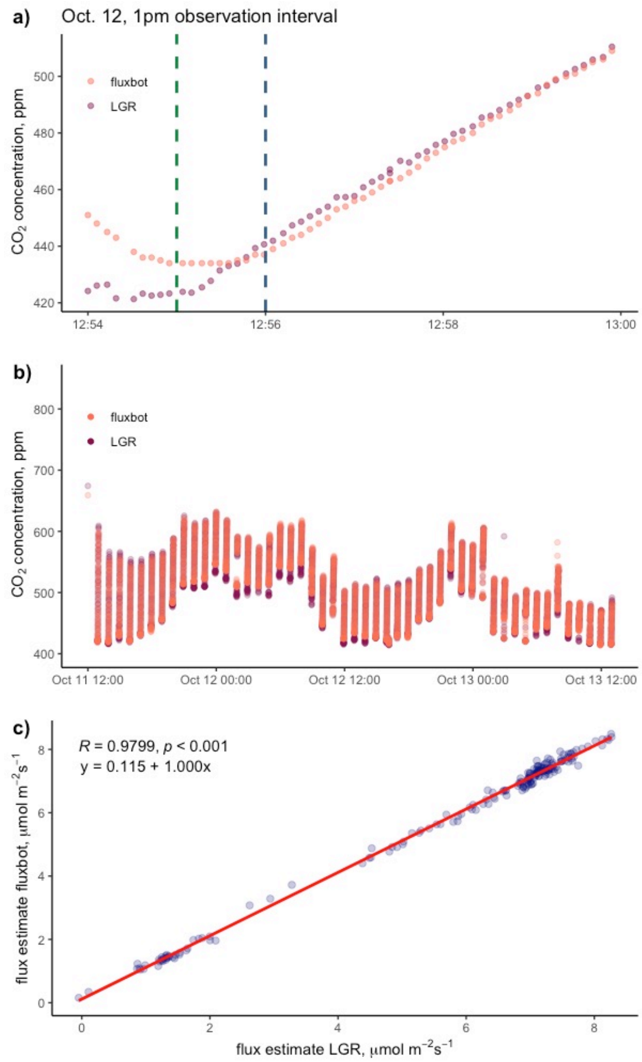

Figure 6: a) A representative hour's worth of paired Fluxbot and LGR raw CO_2 concentration data, taken on October 12th from 12:54 to 13:00. The green dashed line denotes the moment the Fluxbot chamber lid closed (at the 55th minute of each hour), sealing the volume of atmosphere inside; the blue dashed line denotes the minute at which we started the linear and quadratic regression calculations to describe these data streams, with which to then generate flux estimates. b) Raw CO_2 data showing two full days of individual hourly observation intervals (e.g. the data from panel a), but repeated 48 times) in October 2023. Identical to panel a), each observation interval includes data taken by both Fluxbot (pale orange) and LGR (purple) sensors co-located on the same chamber volume. c) Soil carbon flux estimates generated for each paired observation interval using raw CO_2 data from each unit (Fluxbot estimates on the y-axis, LGR estimates on the x-axis).

to a Fluxbot unit, modified with two holes drilled into its chamber side wall, via an 'inlet' and an 'outlet' length of tubing fitted into these holes. This setup created a closed loop of internal chamber volume shared between the LGR's sensors and the Fluxbot's; the internal pump of the LGR drew air from the interior of the Fluxbot chamber through the inlet tubing, and back out through the outlet tubing.

We deployed this dual-system setup on clean (i.e., no plant growth) soil just outside Greeley Laboratory at Yale University for three days in October 2023; we then moved the setup indoors to a climate-controlled laboratory for five additional days, deployed in a mesocosm of clean soil (eight days total). The LGR measured concentration of CO_2 at 1 Hz, while the Fluxbot underwent normal operation at 0.16 Hz.

The purpose of this experiment was to directly compare both ambient CO_2 detection *and* flux estimates calculated from the data collected and transmitted by the Fluxbot, to those calculated from the LGR measuring the exact same volume of air simultaneously. Upon completion of the paired Fluxbot-LGR deployment, we compared the raw CO_2 concentration data collected by each sensor system. We found that the two systems had high amounts of overlap in their detection of raw CO_2 (fig. 6a., b.) and that the sensors for each system showed equilibrated accumulation curves at approximately one minute after chamber closure for each observation interval (fig. 6a.) (possibly due to the different forms of sensor detection for each, as the LGR's CO_2 sensor dynamically "sees" the CO_2 in the internal volume of the chamber as it is pumped past via a flow-through pump system, and the K30 statically "sees" the CO_2 via passive diffusion of the air in the chamber itself). Because this pattern was observed across the majority of observation intervals in the dataset, we determined that flux estimates should be calculated from regressions that encompassed the last four minutes of each five-minute observation interval.

We calculated flux estimates for each observation interval detected by the two systems, as described in section 3.5. (Because the LGR collects meta-data like temperature, pressure, and moisture content of the air that is pumped into its internal volume where the CO_2 sensor is located, and is thus reflective of these parameters inside the LGR and not the chamber volume, we used Fluxbot-generated meta-data when calculating flux estimates for LGR-generated CO_2 data.) We compared temporally-paired flux estimates and determined that the statistical correlation (Spearman) between LGR-derived and Fluxbot-derived fluxes was almost 1:1, with an R^2 of 0.98 ($p < 0.001$) (6c.).

5 IMPLEMENTATION

After replacing the servo motors and encasing the K30 sensors in PTFE envelopes to prevent water damage, we deployed 16 Fluxbot units in a temperate hemlock forest ecosystem site located at Harvard Forest located in rural Massachusetts. The purpose of this deployment was to assess the quality of the data stream, test the efficacy of the solutions to the issues discovered during stress testing, experimentally assess battery life *in situ*, and confirm remote transmission of data from within a rural, canopy-covered deployment location with low levels of LTE connectivity (fig. 7).

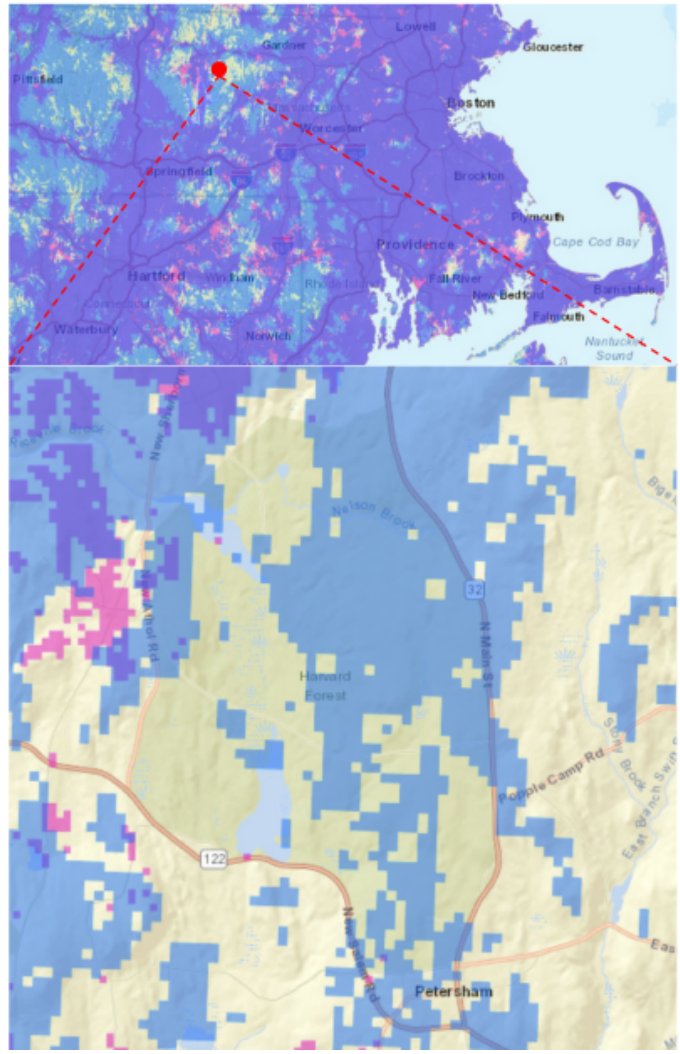

Figure 7: FCC Map of cell coverage over Harvard Forest, where Fluxbots were deployed. Blue regions correspond to AT&T coverage, while pink corresponds to T-Mobile coverage.

5.1 Operational Lifetime Benchmarks

Of the 16 deployed, two Fluxbots malfunctioned within 24 hours of deployment due to a heavy storm that brought extreme rain and water pooling inside of the electronics enclosure. However, the other 14 units functioned as designed until their batteries ran out of charge. This resulted in a measured mean battery life of 317 hours (approximately 13.2 days), displaying an error of 3.86% from the estimated value. Compared to the Fluxbot 1.0, which had a battery life of approximately 24 hours (without recharging via solar panels), this is approximately a 1220% increase in battery life on a single charge, and allows the device to be deployed in environments where solar energy harvesting is not feasible. Back-calculating the average hourly current draw from this mean battery life results in a measured mean hourly current draw of 41.98 mA per hour (displaying

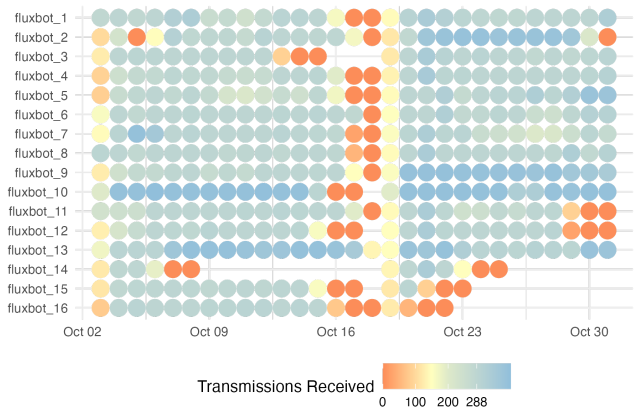

Figure 8: Plot of received data transmissions from each Fluxbot unit deployed in Harvard Forest. Each dot represents a single day of measurement.

an error of 4.07% from the calculated estimate of 40.339 mA/hr). At a rate of 24 flux measurement intervals per day, the Fluxbot array produced (on average) 317 flux measurements at each location on a single charge (approximately 10,144 flux measurements total over the course of the deployment).

5.2 Data Transmission

As shown in fig. 7, the 4G LTE cellular coverage from the carriers utilized by the Boron is sparse and incomplete across Harvard Forest. Figure 8 shows the number of complete data transactions (i.e. data transmissions received) for each Fluxbot unit, each day, for the duration of the experiment. Baseline operation results in 288 daily transmissions (12 transmissions per hour × 24 hours), though more may be used if the Fluxbot recognizes that a sensor is producing faulty values due to its previously-described auto-reset functionality.

Analyzing the number of received transmissions reveals two critical insights with regard to field performance of the deployed Fluxbot units. First, transmission data shows that the entire fleet stopped transmitting between Oct. 17 and Oct. 18, but almost all units resumed normal operation on Oct. 19, reflective of our having replaced all of the battery packs (which were depleted of charge) on Oct. 19. (The cessation of incoming data, and the array having been deployed close to the maximum predicted battery life we had previously estimated in the lab, indicated to us remotely and in real time that the issue was most likely the batteries needing replacement and/or charging). Second, given that the array transmitted data normally until the batteries died (with exception given to the two Fluxbots that malfunctioned due to heavy rain), we conclude that low-quality cellular coverage and closed forest canopy did not meaningfully impede Fluxbot remote data transmission.

5.3 Measured Flux Data

After an approximately one-month deployment in October 2023, we produced 7,005 quality-controlled individual flux estimates (from the original ~10,000 observation intervals) across our array of 16 Fluxbots. To be conservative, we then removed 883 total flux estimates collected by the two damaged Fluxbots which were observed to have been stuck in the "closed" position for extended periods of time. We also removed 12 total flux estimates that were below -0.01umol/m2/sec, under the assumption that such outliers would only occur due to mathematical error (and assuming some level of noise around zero). This resulted in a final dataset of 6,110 flux estimates, collected remotely.

Fluxbots are intended to complement existing commercial chamber systems, given their low price, independence, and reproducibility, all which allows researchers to deploy them at landscape scales (and ask landscape-scale questions). However, for the sake of comparison, a similarly-sized dataset collected with a commercial survey chamber would take a researcher at least 509 hours (assuming a measurement at a single collar takes 5 minutes, not including time to travel between collars). This estimate also does not account for the fact that 24 hours of continuous hourly measurement with a manual survey chamber is infeasible without multiple survey chambers and multiple operators per collar, working in shifts. While commercial auto-chamber arrays can (and do) produce extremely high-resolution datasets in space and time, it is likely similarly infeasible to do so at the large spatial scales represented by our deployment without incurring extremely high costs:with n=16 chambers, we estimate approximately 191,450 USD by summing mean prices for commercial chambers, analyzers, and multiplexer units. Our array of 16 Fluxbots cost 6,064 USD in parts (not including assembly labor), roughly 3% of the cost of a similarly-sized commercial auto-chamber array.

Our dataset captured anticipated variability associated with forest health (healthy or unhealthy), with greater variability observed in the "unhealthy" plot (which has a patchier tree canopy and a more diverse understory) (fig 9a). In addition, and within the two plots, the data demonstrate distinct patterns in daily flux cycles, with higher fluxes generally occurring in midday and afternoon hours when ambient (and thus soil) temperatures are likely to be highest (fig. 9b). This pattern, while also reflecting inter-Fluxbot variability reflective of a highly heterogeneous forest floor, was expected given high-temporal-resolution datasets collected from other temperate forests and in the autumn months[12].

The dataset collected and transmitted by our array of 16 Fluxbots, even with conservative quality control measures in place, captured an impressive range of characteristics associated with soil carbon dynamics: forest health, anticipated small-scale spatial heterogeneity, and repeated, time-based patterns in flux over the course of a 24-hour cycle. The case study was extremely successful, and demonstrates the Fluxbot's utility, particularly when deployed in large numbers at *a priori* identified features, across large areas, and to explore landscape-scale questions at high spatial and temporal resolution.

6 CONCLUSIONS AND FUTURE DIRECTIONS

6.1 Future Directions

While low-cost and open-source wireless sensor networks hold great potential for the field of technology-driven environmental science, there are a number of issues that must be addressed before

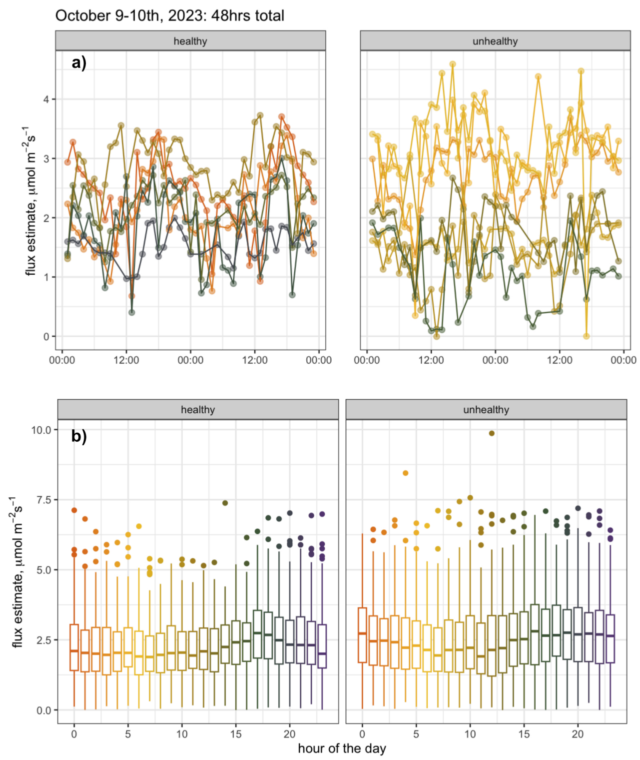

Figure 9: a) A sample of two days' worth of flux estimates from the distributed array implementation test, demonstrating distinct and repeated patterns in flux from midnight to midday and back again, as well as the difference in variability between a healthy and unhealthy forest condition. b) The median and distribution of flux estimates for each hour of the day from the entire two-month implementation test, demonstrating again distinct time-based patterns in flux as well as average differences according to forest health condition.

a solution will be accepted and used by the larger ecology community. While the addition of PTFE envelopes did reduce the amount of water that condensed on the K30 sensors, it did not entirely eliminate condensation. In future iterations, we will design an enclosed rigid case with an insert for a PTFE filter to further insulate the K30's optical path from moisture buildup.

Second, the battery life must be improved, preferably to longer than 30 days - as the largest source of non-intermittent current draw at present is the microSD card used for onboard data logging, we plan to implement a MOSFET-based switching system to intelligently cut power to the microSD card via a GPIO pin on the Boron. Furthermore, while upgrading the servos did largely resolve the issues with opening we observed in the stress test, we did still experience some units becoming unable to open from closed as the battery lost charge. As this is related to the discharge rate of the battery pack, further efforts to reduce overall power consumption will likely alleviate this issue. We plan to implement a bump switch to monitor the lid status remotely to enable remote troubleshooting, as well as a power management integrated circuit (PMIC) to allow remote battery monitoring.

Lastly, after implementing the above changes we aim to make this design directly accessible to researchers through two possible channels. By collaborating with a commercial gas sensing device company, we hope to offer direct purchase (with the sale price inclusive of parts as described here, in addition to labor and troubleshooting prior to shipment). Moreover, we aim to retain the right to offer the ability for university researchers to download the Fluxbot design and parts list directly (e.g. open access); by asking researchers to share their processed data via a written agreement before downloading, we hope to develop a geographically-dispersed network of datasets collected by Fluxbot arrays (see Nutrient Network [2], Oak Ridge National Laboratory soil respiration dataset[1], etc.)

6.2 Conclusions

We tested our design in three stages, iterating on the design after each stage. First, we performed an extensive stress test to study the weaknesses of the design with regard to weatherproofing and servo torque, after which we improved the overall resilience of the system by replacing both the lid servo and introducing a PTFE envelope to protect the K30 CO_2 sensor's optical measurement pathway from condensation. Then, we assessed the performance of a single Fluxbot unit by directly comparing the flux estimates from both the Fluxbot unit and a LGR precision gas analyzer, demonstrating excellent correlation between the Fluxbot flux estimates and ground truth (LGR) flux estimates. Finally, we deployed an array of 16 units in a nearby forest, allowing us to experimentally assess system performance in a real-world field deployment scenario with low cellular connectivity.

This generational update of the Fluxbot resulted in a more widely-useful device that fills a current gap in the market for inexpensive, autonomous, and replicable soil carbon flux chambers; we improved upon the original design by using as many pre-fabricated materials as possible, designing a PCB rather than hand-wiring each Fluxbot unit (increasing inter-unit accuracy and ease of construction), greatly expanding the system's operational lifetime, and (critically) implementing remote data transmission capability. These features make the updated Fluxbot far more useful for environmental researchers and stakeholders, and improves the ability to troubleshoot individual Fluxbots in real time. By adding the updated Fluxbot to the ranks of currently-available soil carbon flux chamber designs (table 1), we have filled a gap: complementing existing high-precision chamber systems with a distributed array of Fluxbots will allow researchers and environmental practitioners to interrogate additional scales of inquiry when exploring a landscape's carbon cycling dynamics.

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