ENTS: Experiences in Co-Designed Environmental Sensing

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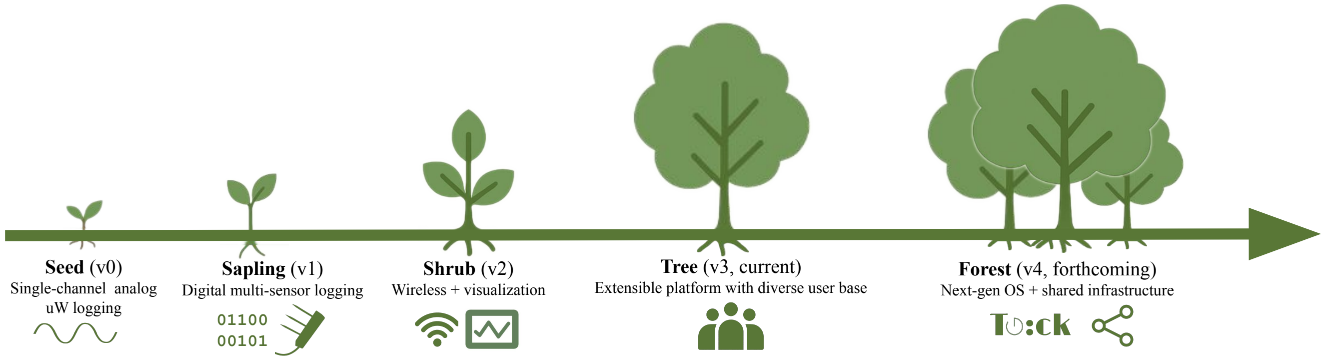

Figure 1: The growth of ENTS from a simple use-case to a widely adoptable wireless sensor network platform

Abstract

Wireless sensor networks (WSNs) deployed in the natural environment offer well-established benefits for prediction, modeling, timely response, and informed decision making in the face of the accelerating climate crisis. To facilitate faster experimentation and deployment, researchers have focused on developing WSN platforms that support rapid prototyping and field readiness. Despite their potential, these platforms have historically seen limited uptake both among domain scientists and the broader IoT research community. In this paper, we present insights gained from the development of ENTS (Environmental NeTworked Sensing)—a WSN platform co-designed with three distinct groups of domain scientists through an iterative development process. We describe the evolution of ENTS from a simple analog measurement tool to an extensible platform actively supporting collaborations with diverse domain experts. We synthesize our experience into a set of design principles aimed at fostering impactful and lasting research partnerships. Finally, we instantiate the outlined design principles for future interdisciplinary sensing efforts, including open-source hardware, firmware, low-cost custom weatherproof enclosures, and a web-based visualization tool.

CCS Concepts

• Computer systems organization → Sensor networks; **• Hardware** → *Power and energy*; **Sensor applications and deployments**; **• Applied computing** → *Environmental sciences*; *Agriculture*.

Keywords

Wireless sensor networks, Wireless sensor network platforms, Field deployments, Co-design, Environmental sensing

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1 Introduction

Wireless sensor networks (WSNs) have delivered transformative insights into environmental and societal challenges, from wildlife tracking to disaster mitigation and precision agriculture. In response, general-purpose WSN platforms have been developed to support diverse sensing research applications while abstracting common challenges like power and communication. Despite a decade of research and a proliferation of hardware and software platforms, most initiatives don't persist. Of the 14 hardware/software WSN platform papers published in SenSys, BuildSys, IPSN, and EWSN in the last 10 years, only 7 have identifiable open-source resources available online, of which only 2 have had an update in the past year (see Table 1). For such a crucial link in the environmental sensing ecosystem, the number of deprecated platforms is startling.

Bespoke sensor networks are all created with compelling use cases. ZebraNet [82], for instance, was a high-impact WSN application that emerged from collaboration between ecologists and electrical engineers. It focused on wide-area animal population tracking to enable more accurate assessments of wildlife movement and inform conservation strategies. Similar interdisciplinary efforts have explored low-cost soil moisture sensing to address agricultural water scarcity [38], or distributed sensing networks for early detection of escalating natural disasters such as wildfires [18]. Across domains, WSN research has demonstrated benefits for wildlife management, disaster mitigation, and resource conservation [4, 25, 41, 71]. Despite the demonstrated benefits of WSN research, most platforms designed to accelerate research and application of WSNs have failed to garner and maintain an active user base of domain science partners. This begs the question: ***why did so many of these WSN platforms die?***

Platform	Venue	Source	Published	Last Updated
Ekho[32]	SenSys	✓	2014	2017
Flicker[33]		✓	2017	2017
Shepherd[27]		✓	2019	2025
Riotee[28]		✓	2024	2025
Buzz/Breeze/BigBen[12]	BuildSys	✓	2014	2016
BuildSense[13]		×	2017	N/A
Pible[24]		✓	2018	2020
RAMP[67]	IPSN	×	2015	N/A
Synergy[3]		×	2016	N/A
Signpost[1]		✓	2018	2018
Eclipse[17]		×	2022	N/A
T-light[16]	EWSN	×	2024	N/A
Ice[65]		×	2024	N/A
Duemer[19]		×	2023	N/A

Table 1: WSN Platform Papers published in SenSys, BuildSys, IPSN, and EWSN between 2015 and 2025. Many are undocumented and most are deprecated.

A key reason many WSN platforms fail lies not in their envisioned applications but in how they are designed, maintained, and supported. Too often, platforms end up as one-off research artifacts optimized for narrow technical trade-offs — such as gains in power consumption or communication range — rather than as living systems meant to serve diverse scientific partners. This is not to say that optimizing for extreme power or communications constraints has no value; such work advances the state of the art and is essential for certain special-case deployments. But those deployments will always require bespoke systems engineered for extreme constraints in cost, power, or durability, and thus fall outside the scope of a general-purpose platform [9, 26, 46, 51, 60, 79]. For platforms intended to serve a broader community, the greater challenge is extensibility. Modular systems—where we use 'modular' in the hardware sense, i.e. having a fixed menu of interchangeable components—have limited degrees of freedom, providing flexibility only within the options anticipated by the original design. Extensible systems, by contrast, assume that new requirements will emerge and provide stable interfaces for adding entirely new functionality, whether they be new sensors, power systems, or communication methods. Without this capacity to evolve, modular platforms quickly become obsolete as domain scientists encounter needs outside the original design envelope. Finally, it is easy for us as engineers to forget that platforms rarely succeed on technical design alone. Outreach and documentation are too often afterthoughts, leaving potential adopters unable to evaluate, trust, or meaningfully extend a system. Without extensibility, sustained support, and active co-design with domain scientists, even the most technically impressive platforms struggle to attract and retain real users.

These recurring challenges raise the question of what it takes for a platform to avoid this cycle and remain useful over time. **In this paper, we present ENTS (Environmental NeTworked Sensing) as an illustrative case of how WSN platforms can evolve differently (See Figure 1).** Many past efforts were ambitious, motivated by urgent scientific questions and sometimes supported by interdisciplinary collaborations, yet structural barriers often hindered their persistence. ENTS offers one perspective on how such challenges might be addressed. Unlike many of its predecessors, ENTS is currently in active use and continues to grow its user community. Over the past three years, it has grown through iterative co-design with domain scientists, expanding from a single-purpose measurement tool into a versatile platform that continues to support collaborations across soil science, biology, and agroecology. It has enabled field deployments in farms, laboratories, marshes, and vineyards. While not a universal solution, ENTS highlights how deliberate extensibility, open-source availability, and sustained engagement with end users can help a platform remain active and adaptive over time. Drawing on these real-world deployments and sustained partnerships, we reflect on what has made ENTS successful as a *living* platform — one that has not only remained active, but continues to attract new collaborators. We highlight three design principles that have guided ENTS's development and may inform future WSN efforts:

(1) *Design for breadth (or, WSN platforms should be over-equipped).* The primary goal of a WSN platform is enabling faster and larger-scale deployments. In ENTS, this principle is reflected in slight over-provisioning: extra sensor channels, standard communication interfaces, and generous power headroom. These provisions allow researchers to prototype quickly across diverse environments without redesigning the hardware [31].

(2) *Prioritize extensibility over modularity.* Many WSN platforms design for modularity [1] by offering a fixed set of interchangeable components users can quickly combine. While flexible in the short term, this breaks down in practice, no preset menu can account for the diversity of real-world deployments. ENTS instead emphasizes extensibility: it provides stable extension

points and documentation that make it possible to add new sensors, power options, and communication methods. This approach has already enabled ENTS to grow from a single-purpose logger into a platform supporting multiple wireless pathways and new sensing collaborations, without redesigning the core.

(3) *Co-design and outreach are primary design requirements for real-world deployment of WSNs.* Co-design is the process of working in close collaboration with domain scientists throughout the design and deployment of a system by aligning the platform's capabilities with their requirements and constraints. Many of the highest-impact examples of prior WSN work were grounded in such partnerships between developers and domain scientists [71, 82]. Building these relationships takes time and commitment, as credibility with domain scientists must be earned. This means undertaking proactive outreach efforts, maintaining high-quality documentation, and fostering collaborative communities to build trust and enable long-term co-design. In ENTS, these practices have been central to its growth, with soil scientists, ecologists, and agroecologists shaping new capabilities through sustained collaboration.

ENTS began as a cost-effective tool for monitoring the energy production of soil microbial fuel cells [48] and has since evolved into an end-to-end deployment platform that combines multi-sensor hardware with supported firmware, data ingestion, and visualization tools (Figure 1). Over successive iterations, ENTS has grown from a simple analog logger into a versatile system that is actively used across multiple domain science collaborations—making it one of the few research platforms to be extended by diverse teams beyond its original purpose. Our contributions lie not in a single novel hardware or networking component, but in identifying and validating system-level architectural decisions that enable sustained adoption and evolution of a WSN platform across heterogeneous scientific deployments. In particular, we show how specific design choices—such as extensibility-first architecture, deliberate over-provisioning of sensing and communication interfaces, and integration of measurement, sensing, and visualization into a stable end-to-end pipeline—that collectively enable ENTS to grow across domains without requiring core system redesigns.

(1) *To advance adoption by domain science partners and facilitate IoT research*, we present the design and evolution of ENTS, a supported end-to-end hardware, firmware, and visualization platform base, developed through an iterative co-design process. ENTS can be extended to meet individual research needs in the lab, field, and transitions in between. All hardware design files, firmware and other software are available in an active and well-maintained open-source repository. Our architecture provides users and developers with a trusted, field-tested foundation.
(2) *To enhance partnerships between domain scientists and WSN developers*, we present a framework derived from case studies and insights learned through our co-design process where our inferences are not grounded in assumptions, but in lived collaboration — each interaction with domain experts refining the design goals of what we set out to build. We share lessons gained from a variety of deployments: soil microbial fuel cells (soil scientists), prickly pear cacti (biologists), and leaf wetness sensors (agroecologists). Our experiences and lessons are not prescriptions, but rather offer guidelines on building long-lived and impactful IoT and domain specific research collaborations.

In Section 2 we discuss the motivating factors behind ENTS, namely, the challenges in applying conventional low-power measurement in the field, and the limitations of current WSN platforms. In Section 3, we present ENTS' evolution in stages. We begin with ENTS' rudimentary Seed/Sapling beginnings as an analog logger, through its evolution to a remote measurement system, and to the current multi-purpose data-logging/visualization enabled fully grown Tree. For each stage, we lay out the background, motivation, and collaborator-in-the-loop design choices. Insights are provided from the lived user experiences (both us and our collaborators) and used to inform the evolution of the next stage. We evaluate ENTS against other WSN platforms and logging platforms that are capable of measuring low-power energy sources in Section 4. We discuss how the outlined design principles and development benefits the larger scientific community. Finally in Section 5.3, we discuss in-progress collaborations and future development efforts to facilitate domain science partnerships.

2 Background and Related Work

Sustainable power has confounded WSN and Internet of Things (IoT) developers for decades [35, 66]. Solar and batteries have become the standard method for powering outdoor WSNs due to the availability of parts and ease of setup. This combination is often touted as environmentally friendly, however, batteries contain toxic materials and require periodic replacement which ultimately contributes to electronic waste. The origin of ENTS was planted in a collaboration with microbiologists investigating soil microbial fuel cells (SMFCs) [37, 48], an alternative low-power energy source. SMFCs convert chemical energy to electrical energy by harnessing the metabolic reactions of endemic bacteria. Among low-power energy harvesters, SMFCs are uniquely positioned at the intersection of biology and embedded systems: microbiologists are drawn to their electroactive bacterial properties, while WSN developers see them as a steady trickle sustainable power source for IoT devices. We initially developed ENTS as a high-fidelity analog logger, to be able to study the µW-levels of power produced by SMFCs, establishing a reliable foundation in low-power research before extending to wireless and multi-sensor capabilities.

Measuring Low-power Sources in the field. Effectively characterizing low-power energy sources (such as SMFCs) in relation to environmental factors requires studying dozens of duplicates in a variety of isolated conditions [20, 21, 76, 77]. Current commercial off the shelf (COTS) and research solutions are cost-prohibitive and do not scale to larger experiments [40, 44]. It is common to first run experiments in the lab, under ideal conditions, to gain an understanding of the possible power before experimenting in the field [73]. Yet, existing solutions cannot be used in outdoor settings without modification to communication and power.

Measuring low-power energy sources is difficult due to the µW-level of power they produce and unintended effects from measurement loading [44]. Desktop data acquisition devices (DAQ) such as the Keithley DAQ6510 [40] are well positioned for lab experiments due to their measurement fidelity. uCurrent [22] and Current Ranger [68] leverage existing measurement hardware by providing an analog frontend to measure nA-levels of current, but need additional engineering to measure voltage and log these measurements.

Several research platforms, such as RocketLogger[44], Ekho [32], and Shepherd[27], have been developed to support the study of edge energy harvesting for IoT applications[34, 47, 70, 83]. These solutions are capable of high-frequency sampling in the 10's of kHz with µV and nA accuracy. However, they are not robust to outdoor environmental conditions, nor do they have built-in support logging data from external environmental sensors. This limits their usefulness in studying power output in relation to environmental factors. The DAQ, RocketLogger, and Shepherd trade higher cost and power consumption to achieve high measurement fidelity. The high sampling rates are unnecessary for environmental deployments where changes are measured in days rather than µs [15].

Existing measurements solutions have the necessary fidelity, but are difficult to deploy outdoors, lack scalability, and do not support additional sensor measurements. This raises the question: how do we develop a more **accessible** platform with enough **precision** for experiments such that domain scientists are willing to adopt it?

Bespoke WSNs and WSN Platforms. Bespoke WSNs are purpose-built for a specific sensing application with fixed hardware components and software implementations. Examples include wildlife tracking [39], wearable health sensors [8], power grid monitoring [41], soil nitrate monitoring [10], etc. The narrow designs of bespoke WSNs are justified by strict requirements in form factor, communication, or sensing method.

In contrast, a WSN platform is designed to improve power, communication, or computation capabilities. They are designed for a variety of sensing applications and can be modified for a specific use case. For example the WSN platform [62] was used to reduce electrical consumption in buildings [36]. Other WSN platforms in academia have abstracted low level complexities like communication protocols, power management, and data storage to provide an out of the box solution to many sensing applications [1, 6, 81].

A popular commercial WSN platform used in academia [63] is the METER Cloud Logger ZL6 [55]. It is vendor-locked, requiring a cloud subscription and is not open-sourced. The ZL6 abstracts nearly all technical complexity, but at the cost of highly limited **extensibility** and cross-platform compatibility. Alternatively, the Particle Platform [61] is an open-source framework, with modular boards and enclosures to develop custom WSN systems. Particle provides the hardware and firmware for measuring sensors. Solutions for visualization and storage are left up to the end user. Therefore, Particle fails at **accessibility**. To our knowledge, no commercial platform offers both the flexibility needed for environmental research applications and the accessibility of an "usable-out-of-the-box" deployment tool for non-experts.

Platforms from academia, such as Signpost and SensorScope, aim to fill this gap, primarily by publishing as open-source hardware/software systems. While this is a step in the right direction, they also have limitations. Signpost is an urban sensor deployment platform that provides energy management and power harvesting, and places a strong emphasis on deployability and modularity [1]. SensorScope was an early WSN platform that grew out of early excitement around the initial success of bespoke WSNs [6, 43, 50, 75, 79]. SensorScope offers a constrained set of environmental attributes rather than from *a constrained set of communication protocols.* This reduces the scope of environmental applications possible [6]. Unfortunately, neither platform have garnered significant partnerships with domain experts; nor have they achieved longevity in continuous use. We believe this is because these systems were not co-designed with users, and were therefore developed with an over-emphasis on modularity rather than extensibility.

3 Design

The design of ENTS was an iterative process to meet the needs of domain science partners. We started by being good at one thing with Seed, and focused on accessibility with Sapling. The next iteration, Shrub, made the platform extensible so that it could be used in a variety of environmental sensing applications. Tree is the current in-use version that has facilitated community partnerships between WSN developers and domain scientists. For each iteration, we discuss the lessons learned and subsequent revisions to the platform.

3.1 Seed (v0)

> *Seed (v0)* is a purpose-built high-fidelity, low-cost analog measurement device to allow scalable experiments with low-power energy sources. **To build an effectual WSN platform, start by being good for one thing, in our case analog measurement.**

ENTS Seed [48] was developed to perform low-power measurements at scale. Seed was a naive solution to the monetary costs associated with measuring µW-levels of power from low-power harvesting systems with a high degree of precision and accessibility. Seed was implemented as an analog measurement device without wireless capabilities, requiring an external logger, similar to uCurrent. It is the basis for accurate power measurement on future ENTS versions. In future versions, we wanted to eliminate the external data logger to further improve the accessibility of the device for our domain science partners.

Precision vs Accessibility. For domain scientists to adopt a new system, substantial improvements in usability, measurement fidelity, and cost have to be made. In fact, it has been observed that experts and other cross-disciplinary teams (environmental scientists, land managers, conservationists, etc.) prefer to use familiar systems, even at the expense of performance or efficiency, rather than switch to a new solution [31]. This hesitance stems from the high cost of instability as any unreliability can nullify *seasons* of data collection, which can include months or years of field work, and irreproducible environmental conditions [31, 42]. ***Insight: In Seed, we observed that some loss in accuracy and resolution was acceptable to make it an approachable and affordable measurement solution for low-power energy sources.***

3.2 Sapling (v1)

> *Sapling (v1)* is a logger for field experiments. **Sacrifices in precision are acceptable for increased accessibility and usability.**

	Seed (v0) **Jan. 2022**	**Sapling (v1)** **Jan. 2023**	**Shrub (v2)** **May 2023**	**Tree (v3) (Latest)** **July 2024**	**Forest (v4)** **2026**
V/I sensing	Analog	Digital	Digital	Digital	Digital
Microcontroller	N/A	STM32	STM32, EPS32	STM32, ESP32	STM32, ESP32
Sensor	N/A	N/A	SDI-12	SDI-12, I2C	SDI-12, I2C
On-board Storage	N/A	FRAM	FRAM	FRAM	FRAM, SD card
Wireless	N/A	N/A	LoRaWAN, WiFi	LoRaWAN, WiFi	LoRaWAN, WiFi
Battery	N/A	N/A	N/A	Li-ion	Li-ion
Visualization	N/A	N/A	V/I, TEROS-12	Any	Any
User Config	N/A	N/A	N/A	Desktop Utility	Web Tool
Enclosure	N/A	N/A	N/A	PVC, PLA	PVC, PLA
O.S.	N/A	N/A	N/A	N/A	Tock
Collaboration	Microbial fuel cells	N/A	Leaf wetness sensing	Cactus Energy harvesting	Robotics, Ecology base stations

Table 2: Comparison of ENTS Platform Versions. Seed began as a low-cost analog measurement tool to study low-power energy harvesters. Sapling was a more advanced digital logging device. Sapling evolved into Shrub, a basic WSN platform. In Tree, ENTS became a widely adoptable WSN platform with a rapidly growing domain science user base. ENTS Forest, is the future generation of ENTS featuring the embedded O.S. Tock.

Through the lessons learned from Seed, we made two key updates to our design: improving analog measurement capabilities, and incorporating digital logging capability through a microcontroller. The analog measurement fidelity requirements remained the same as Seed. A full characterization of measurement characteristics is provided in Section 4.2.1.

Sapling's analog circuitry allowed for differential and bipolar power measurements. Differential measurements allow the voltage and current measurements of individual cells to be isolated when connected in series/parallel configurations. Bipolar measurements allow us to measure negative values so that voltage reversal phenomena can be studied [58]. The move to digital data logging and on board storage grew ENTS from a measurement tool to a logging platform for our domain science partners. These changes sprouted ENTS from Seed to Sapling.

Insight: Adoption requires multiple use cases. Although Sapling provided a reliable data logging platform, transitioning from lab-to-field without wireless communication requires significant human effort. While we were developing wireless communication for ENTS, we came across researchers using biomimetic leaf-wetness sensors [57]. Through a collaboration, they used ENTS as a data logger to easily characterize a new version of their novel sensors and transition to field experimentation.

We observed that leaf-wetness-sensing and SMFC researchers faced similar constraints. Both desired remote monitoring of their field deployments, autonomous logging of power and a variety of sensors, and a data visualization interface. The design explorations for Shrub are therefore guided by the question: *How can ENTS be **extensible** to accommodate a variety of domain specific researchers?*

Extensibility or modularity? When iterating on Sapling, we surveyed WSN platforms and noticed that most optimize for modularity [1, 7, 14]. Modularity refers to "having parts that can be connected or combined in different ways" [54]. For example, abstracting wireless protocols enables cellular or LoRaWAN "modules" to be used interchangeably. Modularity adds flexibility in many systems; if designed well, it can make component replacement and upgrades straightforward.

However, we argue that the emphasis on modularity in WSN platform design has limited potential for growth. Since modularity implies a pre-determined set of components, anything outside of the set makes the system unusable without significant effort to **extend** the platform. When our collaborators wanted to monitor environmental factors such as soil moisture or leaf wetness, none of the available solutions supported both SDI-12 and non SDI-12 sensors. Whether modifying an existing solution or designing a new solution, both incur significant technical overhead.

On the other hand, **extensibility** focuses on the development of a stable core that can be adapted for future uses [14]. RISC-V exemplifies this difference, it is a minimal base instruction set that grew over time to support a wide array of optional, standardized extensions [78]. Another such example of extensibility is the modern day dominance of monolithic kernels [64] over microkernels [45]. Simply put, it is easier to extend a system rather than design to fit into an existing architecture. We derive a key insight that modular platforms have difficulty adapting to new applications they were not originally designed for.

While expanding ENTS to support a broader community of researchers, we realized that incorporating digital logging brought ENTS close to a WSN platform. To complete this transition, ENTS needed only wireless connectivity and broader sensor compatibility. However, as shown in Table 1, many WSN platforms have short lifespans and fail to build sustained user communities. This raises a central question: how can a WSN platform be designed to last?

3.3 Shrub (v2)

Shrub (v2) is the transition from a standalone measurement equipment to an end-to-end WSN platform, including a gateway and cloud infrastructure. ***Extensibility drives a platform's longevity.***

Four key new features make Shrub a WSN platform: SDI-12 sensor interface, non-volatile storage, remote communication, and basic data visualization. We added hardware support for an SDI-12 bus to support environmental sensors from METER commonly used in environmental research. We integrate TEROS-12 soil sensor as an

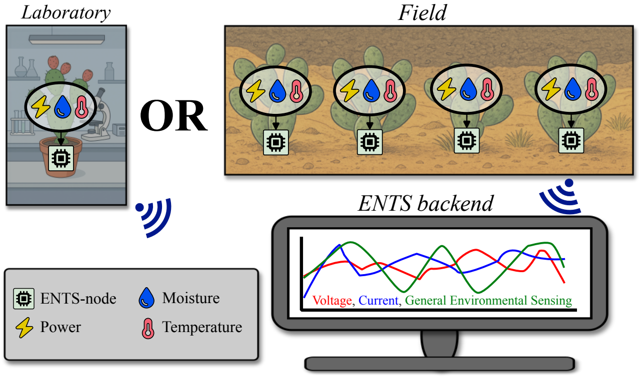


Figure 2: An example use case of ENTS Tree, cacti are monitored in laboratory and field environments to characterize power generation and associated environmental parameters.

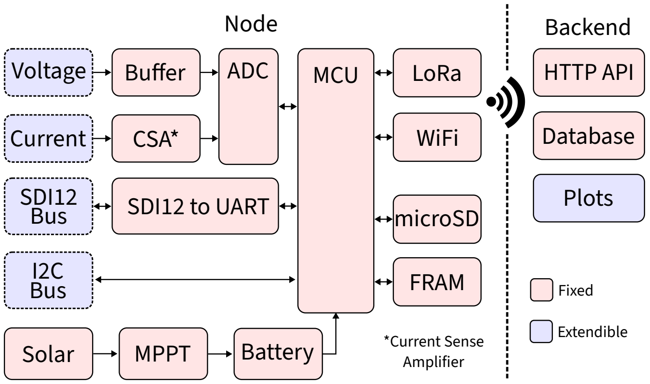


Figure 3: Overview of the Environmentally NeTworked Sensing platform, Version Tree. The platform consists of nodes (left of dotted line) and the backend (right of dotted line). ENTS is designed so that specific modules can be extended from a stable core to meet users' evolving needs.

example to *extend* measurement capabilities to include volumetric water content, soil temperature, and electrical conductivity.

Data is stored on a robust and low-latency buffer before being transmitted wirelessly. All measurements are stored locally until they are validated to have been successfully transmitted and stored in a permanent database. This aids robustness during experiments when data loss from errors is not tolerable. To wirelessly upload data, Shrub (v2) implements both LoRaWAN and 802.11 WiFi. We intend WiFi to be used for in-lab experiments where accessibility and bandwidth is a greater concern than range or power consumption. When transitioning to the field, LoRaWAN can be used where range and power consumption are priority. Both communication protocols encompass the identified needs of domain scientists and do not require further modification. A visualization website handles the storage and rendering of power and TEROS-12 data.

The Myth of Modularity. We assert that the prevailing emphasis on modularity often stems from development without close partnerships with end-users. Environmental deployments typically unfold over weeks, months, or even years, with hardware decisions made well in advance during a careful planning phase. In this context, the ability to swap components, such as wireless communication, at deployment time is highly irrelevant. Domain scientists prefer stable, reliable systems that reduce complexity, not platforms that introduce decision fatigue through a multitude of configuration options [31]. Worse, modularity often introduces new failure points and complicates system extensions with cascading integration issues. Another disadvantage of designing for modularity is that several features may be unimportant, or even wasted. For example, Signpost prioritizes changeable wireless communication [1]. However, protocols such as cellular, LoRaWAN, WiFi, or BLE all allow domain scientists to remotely access data from sensors.

In contrast, extensibility is a design principle rooted in our partnerships. It aligns with longer planning and deployment timelines and enables gradual system growth without sacrificing stability. This model also supports other developers by providing a stable core to build upon, reducing the redundancy of solving the same WSN challenges in isolation. Most importantly, an extensible WSN platform assumes it cannot anticipate all future sensing needs. Therefore it is designed to evolve through additive improvements. ***Insight: We hypothesize that extensibility is critical for any WSN platform to maintain relevance over time, while modularity can be a hindrance to long-term community adoption***

We note that it is possible to use general microcontroller platforms, such as Arduino, as platforms for creating basic wireless dataloggers [2, 11, 23, 29, 80], but the amount of work needed to go from an Arduino board to a usable system is significant. It can be argued that a raw microcontroller platform is arguably more extensible than ENTS. However, a completely generic platform requires significant engineering labor to expand. ENTS offers a middle-ground between completely bespoke platforms and totally generic ones. Though there are existing Arduino-based platforms, they are difficult to build on and extend, as few have source code available, and none, to our knowledge, have been nurtured into an ecosystem with documentation, organization and a robust user/developer community.

3.4 Tree (v3)

> Tree (v3) is our transition to an end-to-end and fully supported WSN platform. ***Co-Design guides pragmatic, usable features while avoiding feature-creep and speculative engineering effort.***

Tree is the current version of the ENTS platform. An overview of the platform is shown in Figure 3, and an example use case in Figure 2. Tree's capabilities are summarized in Table 2. The user specifies deployment-specific settings through the configuration GUI. Each node (Figure 4) is capable of recording measurements on three interfaces: differential voltage/current measurement, I2C, and SDI-12. We chose SDI-12 and I2C for address-based communication, allowing many supported off-the-shelf environmental sensors to be connected.

Data is uploaded wirelessly to a backend API for permanent and robust storage. A website provides generic plots for any sensor allowing researchers to monitor deployments and compare datasets.

This fosters community collaboration and simplifies comparative analysis. The backend also supports data from other logging devices that implement different sensors. An HTTP API interface makes data analysis and visualization easier.

3.4.1 Supporting Efforts. We develop a desktop configuration tool for initial set up to promote **accessibility**. This utility provides a straightforward GUI with embedded features to calibrate analog channels and enable/disable sensors, set upload intervals, or modify API endpoints. These features would otherwise be hardcoded into the firmware, requiring technical expertise to change the configuration.

A major challenge in WSN nodes designed for outdoor use is long-term durability in harsh environmental conditions [82]. Deployments in such environments require a robust enclosure to protect electronics from the elements. We share reproducible enclosures using PVC pipes and 3D-printed inserts to mount the ENTS-node [72]. A battery board with 2×18650 Li-ion cells can be mounted in the enclosure. Traditional energy harvesting sources like solar can be integrated to extend the lifetime of ENTS beyond the initial battery capacity. These features make ENTS a user-friendly and complete platform, and sparked interest for new partnerships (Section 5.3). ***Insight: Successfully developing a WSN platform requires collaboration with potential users and interdisciplinary engineering efforts.***

3.4.2 ENTS-node. The ENTS-node (Figure 4) implements field logging capabilities and integrates high-fidelity, low-power measurement; non-volatile memory storage using FRAM; dual-wireless communication; battery-powered operation; desktop user configuration; web-based data visualization; a custom enclosure; and general-purpose environmental sensing. This over-equipped feature set enables ENTS to operate across diverse environments and support a wide range of domain science partners. Importantly, none of these features have gone unused—a direct result of our close co-design process with end users. By designing in collaboration with researchers, we avoid speculative engineering and ensure that each capability addresses a real need.

In Tree, we extend support for additional environmental sensors by including an I2C bus. Adding support for additional I2C sensors primarily involves adding drivers to support measurements. The measurements utilize the existing pipeline for saving to non-volatile memory (NVM), and uploading to the visualization backend.

We implement the current version of ENTS (v3, Tree) using a Wio-E5 development board, which combines the STM32WLE5JC microcontroller with Semtech SX126X for LoRaWAN communication. A ESP32-C3 is included as a cost effective solution for WiFi communication. Analog power measurements are taken with the ADS1219, a 2-channel 24-bit differential ADC. All captured data is stored on MB85RC1MT FRAM chip, with 125 kB of non-volatile measurement storage corresponding to 4000 measurements.

3.4.3 ENTS-backend. ENTS-backend is a web-based visualization portal where measured environmental variables can be plotted for users to easily view, access, and interpret experimental data. The implementation includes an HTTP API interface to the database and a frontend website to display and disseminate measurements.

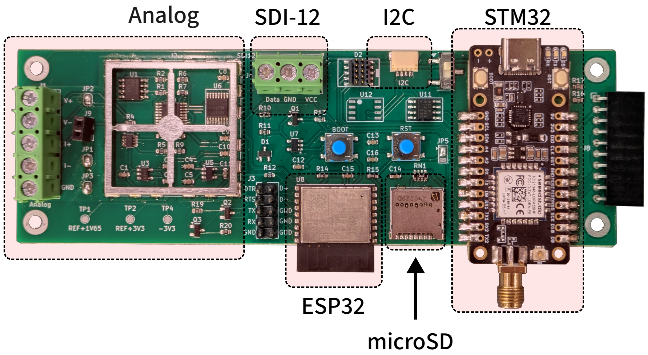


Figure 4: Annotated image of Environmental NeTworked Sensing (ENTS) node. The ENTS node uses the STM32 and ESP32 for wireless communication. It supports measuring analog voltage/current and multiple external sensors connected to either SDI-12 or I2C. A microSD card slot provides mass storage as an alternative to onboard memory.

The HTTP API is implemented with a Flask webserver to provide a **usable** interface for accessing data. A generic *sensor* endpoint is provided to allow for arbitrary integer, floating point, and string measurements. Since the API is separate from the hardware, sensors not in the ENTS infrastructure can also log data in the same place.

Similarly, the functionality of the API can be **extended** to support external visualization and analysis tools. The plots on the website were designed to support a breadth of use cases. Figure 8b was created using the API to correlate day-night and wetting/drying cycles with energy production from cacti in a field deployment.

The website displays plots for each uploaded sensor stream to provide an overview of the most recently uploaded data. We found that visualization of current data is especially useful in adjusting experimental procedures in response to unexpected behavior. Live-streaming of data is also provided to view changes from external stimuli, such as the SMFCs reaction to watering events.

Ongoing experimental data can be compared against historical data to gain early insights and inform future experiments. We host a public instance of the backend that shows real-world data from low-power sources (SMFCs, cacti) experiments. The data shown in Figures 6c, 6b, 8b is publicly available on the website. A central data visualization portal facilitates **community** collaboration, enabling derivation of diverse insights from the shared data. Alternatively the entire stack can be deployed locally with Docker.

Where Community Comes into Play. As we discussed in Seed, adoption of a new platform requires significant improvements over an existing system. Remote data logging and visualization facilitated the adoption of ENTS for monitoring prickly pear cacti by environmental scientists. Through the collaboration we determined that sensor support and ease of use of outdoor deployments were the highest priority. To facilitate these needs, we added support for arbitrary sensors, desktop configuration tool, and waterproof enclosure. We were able to maximize the impact of the platform by supporting the needs of the community. This ensured that the platform would continue to grow through its impactful use.

Researchers interested in studying WSN platforms also benefit from a proven extendable platform. Development of novel ideas can be driven by the current needs of the community to make impactful contributions. Novel implementations, once proven reliable, can be tested in ongoing experiments to demonstrate real-world impact and strengthen contributions. Community is often overlooked in WSN platforms. With ENTS we have shown the benefits to researchers using the platforms and their developers.

4 Evaluation

We evaluate ENTS: Tree both qualitatively and quantitatively against other WSN platforms from academia (SignPost [1] and SensorScope [6]) and industry (METER ZL6 [55], Arduino [5], and Particle [61]). Metrics used in the literature to characterize WSN systems include sensing capacity, form factor, weatherproofing, battery life, power management, and cost. However, we believe that these benchmarks do not fully capture the factors that allow WSN platforms to be used for collaborations between disciplines. Therefore, we also include precision, accessibility, extensibility, and community engagement to offer a holistic means of evaluation. Figure 5 presents the scores of each platform. We demonstrate ENTS in real-world case studies that illustrate its potential as a low-burden, low-power, and highly extensible research WSN platform.

4.1 Deployability: Lab to Field, at Scale

Deployability is a measure of the ease with which a system may be placed, moved, or applied in an environment. Key factors influencing deployability include physical form factor, installation restrictions, environmental robustness (e.g., weatherproofing), power management, and remote communication [1, 6, 14]. When combined with low per-unit cost, high deployability enables systems to scale, encourages community adoption, facilitates more frequent deployments, and ultimately supports platform growth.

4.1.1 Installation. The combination of form factor and weatherproofing provides the installation category.

Form factor. ENTS (116 x 67mm) and Particle (56 x 84.8mm) have the smallest footprint followed by Signpost (42.9 x 30.0 x 8.4cm) and Meter ZL6 (14.9 x 6.3 x 25.0cm). SensorScope consists of base stations nearly 2 m in height. ENTS, Arduino, and Particle's smartphone-sized form factor makes them unobtrusive in outdoor environments, enabling ubiquitous deployments with ease.

Weatherproofing. Outdoor deployments must contend with environmental ingress, particularly from water and dust. Particle, Meter ZL6, and Arduino offer officially rated IP67, IP56, and IP40 enclosures, respectively. Of all platforms, Particle offers the strongest environmental protection, followed by Meter. Both Signpost and ENTS rely on custom-built enclosures that are not formally IP rated; however, ENTS more clearly documents the strengths and limitations of its weatherproofing design [72]. SensorScope's enclosure is difficult to evaluate due to the limited available information. Of all enclosures, Arduino is the only one not water or dust-proofed at all, putting it at risk of environmental-ingress in outdoor deployments.

4.1.2 Power management. Though WSN developers often opt for rechargeable batteries that are replenished with energy harvested by solar or other means, we perform back-of-the-envelope life-time extrapolation assuming SensorScope's 150 mAh primary battery for consistency in comparison. SensorScope can function independently for up to 5 days, Arduino Edge Control endures for 2.5 days, Particle offer competitive power efficiency by lasting up to 2 days, ZL6 lasts a little over a day, and SignPost lasts just a few hours.

The real world power consumption was collected from ENTS in five distinct states summarized in Table 3 with a nominal battery voltage of 3.7 V. With a 5 min upload period measuring from the analog interface and TEROS12, ENTS as a lifetime of 2 days.

State	Current draw	Average time	Energy
Sleep	5.46 mA	300 s	1390 J
LoRaWAN TX	86.5 mA	91.7 µs	29.4 J
LoRaWAN RX	19.9 mA	27.9 µs	2.06 J
Analog/TEROS12	13.1 mA	1.76 µs	0.0852 J

Table 3: Energy usage of ENTS in different modes while being power from a nominally 3.7 V battery. Total energy required is found assuming a 5 min measurement period.

We acknowledge that all the aforementioned platforms, including ENTS, include solar harvesting. Signpost and SensorScope use it as a critical part of their energy infrastructure. The battery lifetime alone does not fully capture the long-term energy viability of a platform, and this comparison should be interpreted accordingly.

4.1.3 Remote communication. ENTS supports two wireless protocols: LoRaWAN and Wi-Fi. The Particle Muon supports these, and cellular (2G/3G/5G) service; Signpost includes 2G/3G cellular, LoRaWAN, and BLE; SensorScope uses 2G/3G cellular exclusively; and METER ZL6 supports Wi-Fi, BLE, and 4G cellular. The Arduino Edge Control only supports Bluetooth out of the box. ENTS does not yet implement any form of cellular communication as our user base has not expressed a need, but due to platform extensibility it could be added. We observed in ENTS Shrub that what ultimately matters is a platform's ability to provide reliable communication in the environments where it is deployed. To date, our partners have preferred LoRa and WiFi for field and laboratory settings, respectively, since neither requires paying for a data plan. Prematurely implementing additional communication modalities risks sinking development effort into unnecessary features.

4.1.4 Cost. Low unit cost is critical to scaling WSN experimentation. The approximate unit cost for a field deployment ready ENTS-node is 100 USD. The unit cost includes the PCBs (50 USD), battery power (20 USD), and waterproof enclosure (30 USD). The approximate unit cost of each device, including enclosure and battery pack, but excluding sensing peripherals, is as follows: Particle Muon (165 USD), Arduino Edge Control (291 USD), METER ZL6 (1000 USD), SensorScope (1500 USD), and Signpost (2000 USD). Experimentation with low-power harvesting technologies requires large number of duplicates, making ZL6, Sensorscope, and Signpost cost-prohibitive. ENTS is the lowest cost of all the options above, making it a financially accessible and scalable solution.

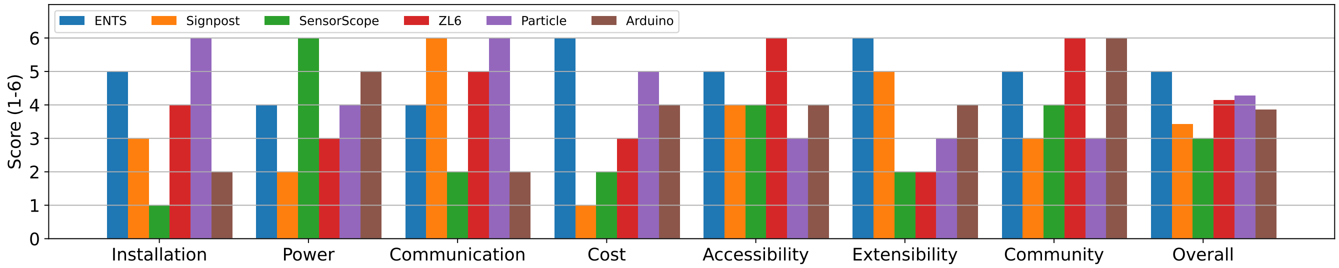


Figure 5: Comparison of the Environmental NeTworked Sensing (ENTS) to other WSN platforms. No other platform has a combination of capabilities that allow the same level of scalability, deployability, and potential for longevity. The scoring system for each category is described under the corresponding sub-heading in 4.1 or 4.2. The Overall ranking is an average of all the categories.

4.2 The ENTS Design Criteria

In this section, we evaluate the WSN technologies on the criteria we developed through our design process: **precision**, **accessibility**, **extensibility**, and **community**.

4.2.1 Precision: Monitoring and logging low-power energy sources. Precision refers specifically to high-resolution analog (voltage and current) measurement for low-power energy harvesters. We compare analog measurement characteristics of ENTS to other high-resolution analog loggers: RocketLogger, Shepherd, Ekho, and a Keithley 6510 data acquisition device in Table 4.

ENTS targets resource-constrained field environments where requirements of sensing range, resolution, and sampling rate are constrained. By reducing these, compared to other platforms, ENTS offers a significantly lower power consumption and enables longer term outdoor deployments.

4.2.2 Accessibility. We qualitatively evaluate accessibility based on the available infrastructure to set up each system and the ease with which users can access and monitor collected data.

Particle requires end-to-end infrastructure development, including sensor integration, data transmission, storage, and visualization, making it the least accessible. The Arduino Edge Control comes standard with short-range wireless through BLE, a suite of sensing communication buses, and back-end analytics. However, incorporating any wireless protocol besides BLE requires integrating a separate MKR board. Further, while the Edge Control does offer an impressive suite of peripheral communication options and libraries, it does not have any particular sensor as standard, necessitating some development for even common environmental science research. Signpost and SensorScope offer inbuilt data collection, but accessing and visualizing requires programming knowledge and API interaction, making them less approachable to those without a technical background. ENTS and the ZL6 platform offer rich remote data visualization capabilities. ENTS supports custom user configuration and provides a "plug-and-walk-away" workflow after initial setup. The ZL6 prioritizes ease of use by abstracting most technical complexity—so long as the user exclusively utilizes METER-brand sensors.

It is worth noting that both SensorScope and Signpost identify accessibility as a key design criterion and succeed in achieving accessibility for researchers in the wireless community. However, their lack of an integrated visualization backend highlights a critical shortcoming of being unusable by domain-science partners, limiting broader impact. We believe that ENTS is the most accessible of the research platforms discussed above, and ranks just behind the industry-standard ZL6. However, where ZL6 relies on closed-source vendor lock, ENTS supports diverse sensors and research goals while remaining approachable to interdisciplinary users.

4.2.3 Extensibility. Extensibility refers to the ease of adding new capabilities that enable new research directions. It is forward-looking: it asks what a platform could sense in the future.

ENTS places extensibility at the core of its design. It supports sensor integration through I2C and SDI-12 buses, and includes workflows for adding new sensors on these interfaces. This lowers the technical expertise needed to expand the platform to meet evolving research needs. Particle and Arduino are designed as *development* platforms, and not application tools. Without built-up engineering experience, it is impractical to develop such development platforms into reliable end use applications. Sensorscope and ZL6 are not extensible and offer a fixed set of 9 and 52 sensors respectively. Signpost requires substantial engineering expertise to develop its modular extensions. A direct point of comparison is the development of Signpost's Ambient Module and ENTS BME280 wrapper on the I2C interface, as both monitor surrounding air conditions. Although the total lines of C code are similar, 164 for Signpost (.c only) and 241 for ENTS (.c + .h), Signpost requires designing a PCB before any code development. The Ambient Module PCB took four electrical engineering PhD students four revisions to execute. The final PCB contained 55 components, 152 pins, and 62 nets. In contrast, the BME280 wrapper for ENTS required one student to write a source and header file around an off the shelf module.

Extensibility, more than any other metric, offers insight into why WSN platforms die. If a platform cannot be easily extended to accommodate new user needs, it will not be adopted. The evolution of Signpost and ENTS demonstrates this. When released in 2016, Signpost supported 7 concurrent sensors and has had no development or use in the last 7 years. On the other hand, in 2024, v2 of ENTS (Shrub) was released with support for 3 concurrent sensors. Through partnerships with other researchers, we now support 10 concurrent sensors as well as features such as actuation and feedback control, all of which are currently in use.

		ENTS	RocketLogger[44]	Shepherd[27]	Mini Ekho [32]	Keithley DAQ6510[40]
General	Size	116 × 67 mm	100 × 68 mm	90 × 55 mm	36 × 22 mm	224 × 387 mm
	Price per channel	50 USD	750 USD	200 USD	45 USD	383 USD
	Idle	15 mW	2 W	1.725 W	N/A	36 W
	Logging	50 mW	2.4 W	1.725 W	140.6 mW	58.5 W
	Channels	1	2	1	1	10
	Sampling Rate	1000 SPS	64 kSPS	100 kSPS	1000 SPS	1 MSPS
Voltage	Range	±2 V	±5.5 V	100 mV to 3 V	8 V	±1000 V
	Resolution	100 µV	13 µV	19.53 µV	NA	10 µV
	Accuracy	5.81 ± 15.5 µV	0.02 % + 13 µV	19.53 µV ± 0.01 %	NA	0.0010 % + 0.0004 %
	Leakage Current	4 nA	5 pA	NA	NA	50 pA
	Noise Floor	5.04 µVrms	5.9 µVrms	10 µV	NA	0.000 15 % + 1 µV
Current	Range	±0.8 mA	±500 mA	0 mA to 50 mA	500 mA	±3 A
	Resolution	119.2 pA	4 nA	381 nA	0.05 µA	1 nA
	Accuracy	83.0 nA ± 658 nA	0.03 % + 4 nA	381 nA ± 0.01 %	NA	0.007 % + 0.006 %
	Burden Voltage	0.33 mV	53 mV	76.1 mV	NA	0.17 V
	Noise Floor	1.53 nA	1.33 nA	0.9 µA	NA	0.0015 % + 10 pA

Table 4: Electrical characteristics of the Environmental NeTworked Sensing (ENTS) node to similar power logging devices, RocketLogger, Shepherd, Mini Ekho, Keithley DAQ6510. ENTS trades measurement fidelity for price, power consumption to make it suitable for scalable field deployments. Its fidelity is sufficient for monitoring low-power energy sources.

ENTS does however have limits to its extensibility. Right now each ENTS board supports the following sensing inputs: analog, I2C, and SDI-12. Analog is limited to one input at a time, with a range of ±2 V. I2C and SDI-12 are each limited to their respective protocol-defined maximum peripheral counts. We are considering adding SPI in the future.

4.2.4 Community. In this section, we compare the WSN platforms on their adoption rates and interactions with their user community. ENTS actively maintains partnerships with environmental scientists by implementing novel sensors to support their experiments. Meter's ZL6 ecosystem has the largest adoption in the soil science community, becoming the de facto standard used in experiments [63]. In our experience, they actively collaborate with their users, demonstrating the importance of domain-science partnerships. Arduino is widely known development platform used in a variety of projects among both engineers and hobbyist resulting in significant community documentation, though much of that documentation is not necessarily relevant to the Edge Control product. Particle has application in asset tracking, preventative maintenance, and equipment monitoring, but lacks adoption from the scientific community. SensorScope and Signpost have no known community users. Although ENTS ranks behind ZL6 in adoption, our highly-engaged and invested community is continuously growing, which aligns with long-term research impact.

4.3 Case Studies in Low-power Research

We deploy ENTS to measure the harvested power and corresponding environmental conditions from SMFCs and prickly pear cacti in collaboration with environmental scientists. Additionally, we demonstrate extensibility to non-sensing applications with a demo irrigation site. Through these real-world applications, we demonstrate that ENTS enables precise and scalable experiments that serve the needs of two distinct communities of researchers.

While these examples do not encompass all potential applications of ENTS, they highlight the platform's strengths and limitations, offering direct feedback from end users.

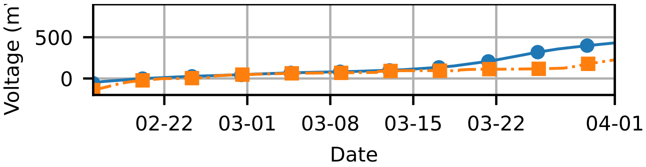
4.3.1 SMFCs at scale. Soil-based microbial fuel cells have gained interest as both ultra-low-power energy sources and biosensors for soil health. However, experimental progress in this area has been hampered by the limited scale of deployments. Most prior work involves only a handful of cells, restricting the ability to develop robust models for power output or to correlate electrical signals with soil health indicators, such as organic carbon content.

To address this, our collaborators deployed 18 SMFCs using samples from three different soil types in open and closed circuit configurations. (Figure 6a). This deployment was the first test of a broader multi-institutional study involving researchers across several universities, each working with their native soil samples. ENTS made this scale of experimentation feasible. ENTS was 13× and 270× cheaper compared to the industry standard solutions using either Keithley and Rocketlogger hardware. Further, the system's low setup overhead, automatic data aggregation, and built-in remote monitoring capabilities allowed researchers to deploy and manage the experiments with minimal technical burden.

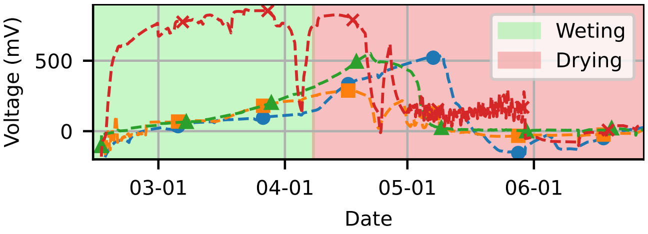
Figure 6b shows the expected open circuit incubation traces for SMFCs. There is a high degree of variance between cells in the same group of local soil. The scalability of ENTS allows for multiple replicates in experiments for statistically significant results. Figure 6c shows the response of cells to wetting and drying periods. SMFCs constructed with different soil types had differing responses to their power output. This can be attributed to each soil's unique characteristics. Scalability of ENTS allowed power to be collected from multiple replicates of SMFCs in various soils.

4.3.2 SMFC Field Experiment. Soil-based microbial fuel cells have drastically different power outputs between lab and field environments. In lab a power output of 100 µW can be achieved, while

(a) ENTS monitoring 18 SMFCs to characterize open vs closed circuit behaviors



(b) Soil-based microbial fuel cells startup trace.



(c) Soil-based microbial fuel cells water reaction.

Figure 6: Plots showing soil microbial fuel cell voltage measurements from lab experiments are shown in 6b and 6c. The integration of high-fidelity analog measurement, environmental sensing, and visualization makes monitoring such low-power energy harvesters straightforward and accessible.

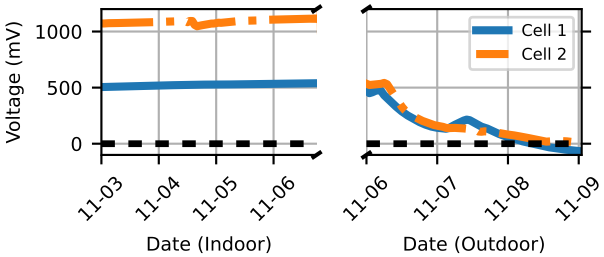
1 μW can be expected in the field. To demonstrate ENTS facilitating lab-to-field transition of experimentation, we collect open circuit voltage traces of two SMFCs from in-lab incubation into a simulated irrigated farm environment. The cells were constructed and incubated until they reach steady state open circuit voltage. (Figure 7a). After 2 weeks showing steady state behavior, they are moved into drip-irrigated raised beds (Figure 7b). The ENTS-nodes were put in waterproof enclosures and configured to upload via LoRaWAN.

Figure 7c shows the voltage, current, and power traces for the cells. The cells showed a large decrease in voltage output due to the less favorable volumetric water content and temperature conditions in the field. The deployment highlights the needs for a WSN platform that facilitates lab-to-field deployments when researching low-power energy sources. Using the same proven platform ensures reproducibility and accessibility for domain science partners.

4.3.3 Cacti Energy Harvesting. We collaborated with environmental scientists exploring energy harvesting from prickly pear cacti (Opuntia streptacantha). These plants are able to generate electrical

(a) SMFC indoor incubation

(b) SMFC outdoor deployment



(c) Open circuit voltage during the transition from lab-to-field.

Figure 7: ENTS monitoring soil microbial fuel cells from lab to field. The difference between indoor and outdoor voltage demonstrates the importance of facilitating the lab-to-field transition. ENTS enables *scalable* experiments and *community* collaboration with in-lab and field studies.

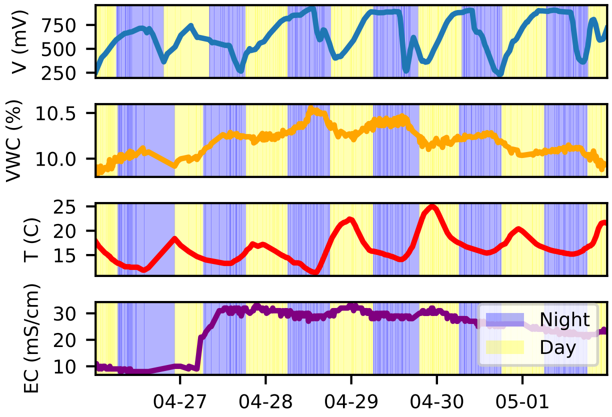
power through the Crassulacean Acid Metabolism (CAM) photosynthesis pathway [49], a process unique to plants in arid environments. Power production is observed when differential lighting (one side of the cactus pad is illuminated and the other is shaded) creates a bioelectric potential, akin to a "living solar panel".

ENTS enabled researchers to investigate this phenomenon in the field. As shown in Figure 8b, ENTS records harvested voltage which is correlated with environmental variables (volumetric water content (VWC), soil temperature, and electrical conductivity (EC)) captured by TEROS-12. This field deployment with the ENTS enclosure connected to the cacti is shown in Figure 8a. The clear cyclical pattern of the open-circuit voltage can be attributed to CAM photosynthesis. During the night when temperatures are cool, cells open to capture CO2, resulting in a sharp decrease in voltage. During the day, when temperatures are warm, stored CO2 is broken down, resulting in a rise in voltage. This is supported by the correlation in soil temperature, and absence of correlation in VWC and EC. The extendability of ENTS allow for measurements of multiple phenomena to support our domain science partners.

4.4 Irrigation System

In addition to sensing applications, ENTS is capable of being extended to actuation and control. We developed a fully functional autonomous irrigation system managed by a few ENTS boards and installed it in raised beds with kale and flowers as shown in Figure 9a We measure the volumetric water content of the soil, water flow rate, and water pressure. We implement hysteresis based control of water flow via a solenoid valve - when the VWC falls below a

(a) Deployed cacti



(b) Sensors plots

Figure 8: Plots showing voltages and soil-moisture measurements from cacti on the farm are shown in 8b. Our visualization platform makes it easy to notice correlations between the voltage and day/night cycles.

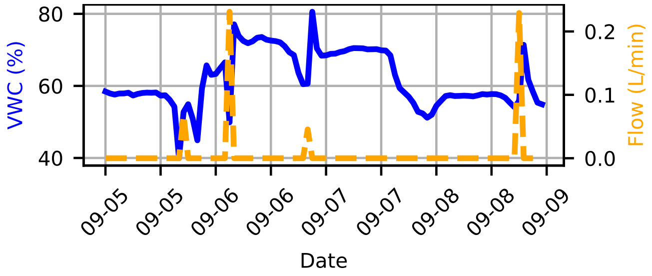
lower threshold the raised bed is irrigated until it reaches an upper threshold. Flow rate and water pressure are regularly monitored to ensure no leaks. A plot showing the irrigation over time is shown in Figure 9c.

Additional sensing and actuation is implemented by re-purposing GPIO pins and sensing channels. The website provides a universal interface for accessing sensor data collected from multiple nodes. An external python script automates the system through a sensor based feedback loop. This deployment extends the capabilities of ENTS to include mechanical actuation and feedback control. Automated experiments like monitoring nitrate concentrations [10] or sensors that require mechanical actuation can now be accommodated. An example is a soil penetrometer, which needs to be pressed into the soil at sampling time for a reliable reading.

5 Discussion

We close with higher-level thoughts on effective, long-lived cross-disciplinary partnerships. We then discuss the benefits to WSN research of ENTS as an open-source academic resource as well as some of the pragmatic challenges of offering sometimes 'product-like' support to domain science partners from an academic setting. We acknowledge that our insights may not be universally applicable; we present them not as definitive solutions, but as points for discussion within the broader community. We encourage researchers to continue discourse as they test and challenge our insights across contexts.

(a) Sensor (b) Valve



(c) Flow rate and soil humidity vs time

Figure 9: Beyond traditional sensing applications, ENTS is capable of extending to actuation and control. Demonstrated by drip irrigation driven and monitored by ENTS.

5.1 Collaboration encourages development

ENTS has demonstrated the benefits of collaboration between WSN platform developers and domain scientists. A symbiotic relationship exists between the disciplines. WSN developers can test novel WSN technology in real-world scenarios. Additionally, developers get direct feedback on challenges faced when using WSNs. Domain scientists get access to systems that facilitate novel research. So far, ENTS has fostered a **community** of multidisciplinary researchers investigating SMFCs. The large-scale experiment shown in Figure 6 was made possible through the collaboration of engineers to develop ENTS and domain scientists to effectively plan the experiment.

During the development of ENTS we found the domain scientists are concerned with the **precision** and **accessibility** of their logging devices, with this being reflected in the proposed design criteria. It doesn't matter how advanced the measurement method is if it's inaccurate. Similarly, domain scientists would rather choose platforms that are easier (i.e. Arduino) to use over platforms that are technologically better, but more difficult to use. WSN developers need to ensure robust accuracy before the start of an experiment, or else trust in the device and collaboration will fall apart. We have found that the extra effort to ensure **accessibility** is succeeded by access to first-hand knowledge from domain scientists.

Platforms such as Arduino [53] have seen widespread adoption because of the minimal amount of development required to extend the functionality of a microcontroller. However, Arduino-developed systems struggle with robustness and completeness. It's easy to take a measurement from an Arduino-compatible sensor, but significantly more effort to build a system to reliably collect data in a format that can be easily used in further analysis. ENTS was designed to be **extensible**, but is lacking in ease of use to do so. As part of a future migration to TockOS (See Section 5.3.1), we aim to improve to extensibility to allow for easier integration of new sensors.

5.2 Building and Supporting an Open-Source Ecosystem

ENTS is an academic and open-source tool. 21 people have contributed to the project including undergraduates and graduate students from several universities and Google Summer of Code. Table Table 5 shows the contributions to each of the individual open source repositories. ENTS' success in collaboration and evolution can be attributed to open-source hardware and firmware.

Metric	Hardware	Firmware	Visualization
Internal Contributors	6	7	10
External Contributors	0	2	5
Commits	404	1259	1158
Forks	0	4	18

Table 5: Summary of contributions across open-source hardware, firmware, and visualization repositories. Internal contributors is anyone within the authors universities. External is everyone else. Metrics for hardware are noticeably lower due to hardware fabrication requirements.

Maintaining an open source project requires a significant time investment. Without application scope outside the original 'paper', there is little reason to continue development. Lack of maintenance is why most defunct platforms identified in Table 1 faded. Continued purposeful collaboration with the **community**, as identified in Section 5.3, ensures consistent growth. The larger the community, the better ENTS will be maintained and facilitate new research.

5.3 Future Work (v4, Forest)

ENTS is a living system, and the next phase of ENTS' growth is Forest. Forest will improve the stability and security of platform for WSN developers and domain scientists.

5.3.1 Migration to TockOS. TockOS is an open-source, embedded operating system that is written in Rust and designed "for running multiple concurrent, mutually distrustful applications on low-memory and low-power microcontrollers" [74]. TockOS is currently used across academia and industry by the likes of Microsoft[69] and Google[30] for security modules and also in safety-critical automotive systems[59]. TockOS on ENTS opens opportunities for shared ownership of sensor networks with applications in environmental research. Institutions would be able to co-own or share hardware in the field, with multiple isolated experiments being able to run simultaneously on a single device. TockOS's architecture ensures that individual experiments cannot disrupt others through crashes or unauthorized access to collected data. This pooling/sharing of hardware sensor resources would improve accessibility to environmental research. TockOS also provides a mature operating system that WSN developers can leverage for novel research on ENTS. Existing deployments would provide real-world applications for developers to benchmark their implementations.

5.3.2 Digital Twin for Agriculture. The "digital twin" concept is gaining traction within environmental and infrastructure monitoring communities [52, 56]. It involves virtually reconstructing an environment to enable advanced simulations of intervention outcomes. The **extensibility** of ENTS uniquely positions the platform to bridge visually reconstructed terrain with in-situ soil measurements. Measurements taken by ENTS can be used to dynamically update the digital twin model using sensor fusion techniques. ENTS enables digital twins capable of estimating 3D soil physics, plant-soil interactions, chemical treatment outcomes, crop yields, and more. The dynamically updated agricultural digital twin that supports more accurate and actionable agricultural management.

5.3.3 Servers for Wildspace Research. A wide range of wild spaces are owned and preserved by academic institutions for research purposes, including the UC Natural Reserve System, the NSF's Long Term Ecological Research (LTER) Network, and the University of Michigan Biological Station. These reserves typically include a field base station with electrical and wireless infrastructure, alongside large tracts of undeveloped land for ecological study.

We hypothesize that the new capabilities introduced in ENTS Forest could support a distributed, multi-user sensing layer across such sites. Rather than deploying bespoke WSN or data acquisition platforms for each new experiment, multiple research groups could "lease" ENTS nodes already distributed across the reserve. These nodes could be reconfigured or extended for their particular sensing goals. Sharing logging hardware would increase accessibility to experimentation at these ecological research sites.

6 Conclusion

We trace the evolution of ENTS from its early "Seed" prototype to its current "Tree" revision, highlighting how each iteration shapes WSN design principles. ENTS is a well-maintained open-source environmental WSN platform that serves as a robust tool for current deployments and a foundation for future research. We derive a design framework grounded in real-world experimentation and interdisciplinary collaboration through our development process. We share the design experience in the hope of encouraging effective domain science and WSN developer partnerships, and to move future research in a new direction, one that prioritizes active co-design, longevity, and accessibility.

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