TECHNOLOGY IN ECOLOGY

Getting Started With Sensor Networks in Experimental Ecology: Pitfalls and Pratfalls

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Tremendous growth has occurred over the past fifteen years or so in the development and use of sensors and associated technological infrastructure in ecological field research (Porter et al. 2009). Of course, ecologists have been using sensors in a monitoring context for decades. Instrumented meteorological stations, for example, are commonly used in terrestrial systems to collect high-frequency measurements of air temperature, soil moisture, and other climatological parameters, while multiparameter sondes have been used extensively in aquatic systems to collect physicochemical data for assessing water quality. Sensor technologies are also deployed by researchers interested in monitoring and comparing ecological systems within an organized network, such as the National Ecological Observatory Network (NEON) or the Global Lakes Ecological Observatory Network (GLEON). Flux towers dot the landscape. However, sensors are increasingly being used in combination with associated cyberinfrastructure as tools that integrate data collection, processing, analysis, and visualization in experimental contexts. Here, we focus on the use of terrestrial sensor arrays, defined as multiple sensor systems (e.g., a suite of temperature, moisture, and CO_2 probes), that can be deployed to generate integrated measurements of ecological phenomena (e.g., soil CO_2 efflux) at high temporal resolution in manipulative experiments (Fig. 1). It is from this perspective that we are writing our personal experience using sensor technologies in ecological research.

It is worth beginning by explaining a bit how we got here. I (SLC) was the original Program Director for NEON at the U.S. National Science Foundation (NSF). NEON was conceived as a distributed ecological observatory comprised of a network of sites that would be highly instrumented with flux towers and environmental sensors, all of which would collect the same variables in a standardized way to document environmental change “at the continental scale.” This helped convince me that sensors and sensor networks were the wave of the future for comparative ecological research. Upon my arrival as a faculty member at the University of New Mexico (UNM) and the Sevilleta Long Term Ecological Research (LTER) program, I had the opportunity to establish

Fig. 1. CO_2 probes in the Monsoon Rainfall Manipulation Experiment after a simulated monsoon storm in the Sevilleta National Wildlife Refuge, New Mexico. This sensor array also includes a soil moisture probe and two soil temperature probes that are not visible in the photo. CO_2 levels at three depths along with soil moisture and temperature measurements can be used to calculate soil respiration at fifteen-minute intervals. Photograph by Renee Brown.

several new long-term climate change experiments in desert grasslands (e.g., Thomey et al. 2011, Collins et al. 2017). Given that dryland systems are strongly controlled by abiotic drivers, especially temperature, precipitation, and soil moisture, it seemed only logical to instrument these new experiments with sensor arrays.

Long-term research sites, such as LTERs and biological field stations, attract researchers from multiple disciplines to a common location, which can often lead to collaboration. At the Sevilleta LTER site, located at the Sevilleta National Wildlife Refuge (SWNR) in central New Mexico, we began using sensor networks through the convergence of three events that occurred between 2003 and 2006. First, we were asked to serve as a test bed for wireless technology called the Sensor Web that was being developed at the NASA Jet Propulsion Laboratory (Delin et al. 2005). Since these sensor pods communicated with each other wirelessly, they were particularly appealing because their placement did not require a physical connection to a datalogger. The Sevilleta site not only provided the Sensor Web engineers an opportunity to assess sensor durability and functionality in our harsh arid environment, but also allowed us to use the Sensor Web in a research capacity, specifically to quantify microclimates under different species of shrubs (Collins et al. 2006).

About a year later, with NSF funding, we established the Sevilleta Wireless Research Network (SevWRN), a large-scale wireless telemetry cloud that enabled us to enhance the frequency and volume of data collection from our research sites and to quickly determine issues with sensor instrumentation, thereby improving overall data quality. SevWRN was initially set up to transmit data from four research sites located in the eastern part of the SNWR; however, we have grown the network substantially over the past fourteen years to provide real-time automated data acquisition from nearly fifty dataloggers and thousands of sensors located at meteorological stations, eddy covariance flux towers, and manipulative field experiments in the SNWR and beyond. Operating the SevWRN has at times presented some unique and interesting challenges, but more importantly, it has provided invaluable insights about using technology in the field. In addition to lessons in environmental protection and the appropriate sizing of photovoltaic systems, we learned it was often more cost-effective to spend more at the outset for equipment that could withstand our harsh environment for longer periods of time. Needless to say, this network annually saves thousands of miles of driving and hundreds of person hours that would otherwise be invested in downloading data onsite, while also allowing remote notification and troubleshooting when equipment failures occur.

Finally, as we were designing a new climate change experiment, the Monsoon Rainfall Manipulation Experiment (MRME), Mike Allen (UC Riverside) sent over his then graduate student, Rodrigo Vargas, with a box full of CO_2 probes (Fig. 2). Mike had some prior research projects in the SNWR, and he was one of the scientists associated with Center for Embedded Network Sensing (CENS), an NSF-funded Science and Technology Center at UCLA. As part of that effort, Mike and Rodrigo had successfully begun to monitor soil respiration at the James Reserve in California using sensor arrays (Allen et al. 2007) and they wanted to determine their utility in an experimental context. After some fits and starts,

Fig. 2. Rodrigo Vargas and Scott Collins discussing the use of CO_2 sensors for high temporal resolution measurement of soil respiration in the Monsoon Rainfall Manipulation Experiment in the Sevilleta National Wildlife Refuge, New Mexico. Photograph by Renee Brown.

we ultimately purchased sensor arrays for all replicates in MRME (e.g., Vargas et al. 2012) and, later, added similar sensor arrays in two other NSF-supported climate change experiments at Sevilleta. For someone like me (SLC), whose prior research had depended on technology no more complicated than tape measures and clipboards, the installation and use of ecological sensor arrays and dataloggers, and the data streams they yielded, presented a steep and formidable learning curve that could only be circumvented through collaboration. Fortunately, I was surrounded by talent.

I (RFB) was first introduced to sensors and sensor networks when I was asked to maintain the Linux computer that interfaced with the Sensor Web at Sevilleta. At the time, I was the systems administrator for the Sevilleta LTER, so this task naturally fell within my responsibilities. Shortly thereafter, I became intimately involved with the SevWRN as I continued to develop new technical expertise. My early involvement in these projects quickly developed into a passion for using technology to support ecological research in the field. Hiking mountains and supporting technological infrastructure in beautiful places few have the opportunity to visit, much less work? I couldn't have asked for a better job!

Meanwhile, as I pursued an undergraduate degree in computer science, I participated in a year-long seminar class that was a collaboration between the UNM biology and computer science departments. This class highlighted the reality that computer scientists and ecologists needed to work together to understand technological, as well as biological, capabilities and limitations. In 2006, SLC sent me to a meeting at the James Reserve to learn about "wireless sensors." I arranged a visit to CENS prior to that meeting, where I met with Deborah Estrin (CENS PI) and her laboratory of primarily computer scientists. CENS was developing a variety of wireless sensors, similar to the Sensor Web, but open-source, and therefore, more accessible to the academic research community. I came to the meeting at James Reserve only to find out that the sensors I was sent to learn about were not in fact wireless at all. There, I was introduced to Rodrigo, where I learned about the soil CO_2 sensors that we ultimately deployed at Sevilleta.

Initially, we deployed the soil CO_2 sensor arrays in four plots in MRME. Unfortunately, the mostly-plug-and-play technology that had worked so well in the more temperate James Reserve did not fare as well in our harsh, hot, dry environment and we were unable to generate any useable data from those sensor arrays during the first summer of the experiment. We subsequently outfitted the site with more robust instrumentation that required more advanced knowledge of datalogger programming, electronics, and photovoltaic power arrays. During 2007–2008, we obtained reasonably good data from our sensor arrays, but continued to struggle to generate usable data from the soil moisture probes, which were designed for agricultural applications, not dry desert soils.

During the 2009 ESA meeting, a lightning-caused wildfire wiped out MRME and our nighttime warming experiments (Fig. 3). While unfortunate, it provided the opportunity to redesign and improve both experiments, while adding CO_2 sensors to the latter. We bought even better, more expensive sensors that finally performed well in our soils. Yet, we continued to struggle with noisy data from the CO_2 probes. We'd already learned that these particular sensors required significantly more power than any of the other sensors in our experiments, but what we didn't know was that they were particularly susceptible to voltage drop, meaning that sensors located further away from the photovoltaic system generated noisier signals. Upon redesigning our power systems to meet the demands of our sensor arrays, we finally were able to generate clean, usable data that we could use to examine the effects of our experimental manipulations on soil respiration.

Fig. 3. Sensor arrays after a lightning-caused wildfire burned through the Monsoon Rainfall Manipulation Experiment in the Sevilleta National Wildlife Refuge, New Mexico. The fire occurred during the 2009 ESA Annual Meeting held in Albuquerque, New Mexico. Photograph by Renee Brown.

In addition to providing high-frequency data, sensor technologies can also be used to automate control of experimental infrastructure. For example, at our nighttime warming experiment, the roll-in and roll-out of motorized thermal blankets is automated by a datalogger programmed with a polynomial equation fitted to local sunrise and sunset times. However, precipitation, particularly in freezing temperatures, as well as high winds, can easily damage this delicate infrastructure. So, the datalogger contains additional programming that uses wind speed and precipitation data generated by a co-located anemometer and rain gage to roll-in the warming blankets during adverse nighttime weather conditions.

As NEON comes online, we are promised high-resolution data streams from excessively well-calibrated sensors but take all of that with a grain of salt. Sensors can generate lousy data or even periodically fail for a variety of reasons that include environmental causes (e.g., rodents chewing through cabling or UV degradation), or electrical issues. Also, some sensors require more attention than others, such as the soil CO_2 probes, which require a time-intensive recalibration process every six months in order to prevent sensor drift. And then, there are those unfortunate events you can never really anticipate, much less imagine. Our nighttime warming experiment has been especially plagued by disastrous events, including repeated tumbleweed invasions (Fig. 4), ravens poking holes with their beaks in our thermal blankets, and perhaps the oddest of all, the death of a Barbary sheep caused by feral dogs.

Furthermore, collaboration with technological staff is essential when using sensors in ecological research. Most ecologists aren't trained in wiring and programming dataloggers, deploying sensor networks, wireless telemetry systems, or structured databases, and the development and documentation of gap filling algorithms and rigorous QA/QC procedures is needed to ensure data quality and continuity. Finally, we recommend managing your expectations. When using the latest and greatest technologies, be aware that most sensor systems were not developed for or tested in particularly harsh environments. Do not believe anyone that tells you their system is plug-and-play.

Despite these challenges and various demonic intrusions, using sensor technologies in ecological research is well worth it. Even though we've experienced various struggles with our sensor networks, our fits and starts were educational for us as well as for those who developed the technology. Continuous, high temporal resolution measurement of environmental parameters is essential for variables like soil respiration that respond rapidly to environmental drivers. In that regard, we recommend oversampling because data storage is cheap and high temporal resolution datasets are more valuable to modelers.

We end by pointing out two future challenges. In terrestrial ecosystems, we are still limited by wires. This may not be a big deal for establishing a meteorological station, but cable length limitations can

Fig. 4. Tumbleweeds gathering inside the metal frames that support the thermal blankets that would otherwise roll out to trap heat and elevate nighttime temperatures in our nighttime warming experiment in the Sevilleta National Wildlife Refuge, New Mexico. Photograph by Renee Brown.

spatially constrain experimental design. Thus, there is a tremendous need for the development of robust, low-power, long-range wireless sensors for ecological research. Secondly, along with cyberinfrastructure, "smart sensor" technology can be used to adjust sensing frequency on the fly. So, rather than have sensors measure once every fifteen minutes whether you need it or not, the system could be programmed to increase and decrease sampling intervals on an event-driven basis in response to the environmental variables being measured. That is, sampling frequency could be increased on the fly when a rain event occurs. Doing so could improve issues surrounding power-hungry sensors; however, irregular sampling intervals might create some interesting statistical challenges. Nevertheless, in our view, the benefits of deploying high temporal resolution sensor arrays in experimental contexts greatly outweigh the challenges and doing so presents many new and exciting opportunities, all of which will greatly improve our understanding of dynamic ecological systems.

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