Deployment of a Large-Scale Soil Monitoring Geosensor Network

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Abstract

We provide an overview of our practical experience with developing a distributed sensor network to monitor soil response to climate change and increase our understanding of the complex interactions of the surrounding ecological, biogeochemical and meteorological processes. The network consists of seven sites with unique topographical, and land-use characteristics, spread across a large area in the state of New Hampshire (US). The system was designed to measure soil moisture, soil $\text{CO}_2$ efflux and make other ancillary measurements (air temperature, precipitation, wind speed etc.). The system design encompasses sensor and hardware selection, customization and the overcoming design constraints such as the need to operate a power hungry sensing system at remote locations with access only to solar power. The data we collect streams to the web as an outreach and teaching resource, provides input to ecosystem models used to predict how ecosystems in the region will respond to climate and land-use change, and directly monitors soil properties and processes in a changing climate.

1 Introduction

Field measurements are a critical component to our increased understanding of the environment. Studying soils and processes occurring in them allow us to increase our understanding of ecological, biogeochemical and meteorological processes occurring in the surroundings. Carbon stock present in soil is a critical component of the global carbon (C) cycle and thus affects global climate, while soil moisture plays an important role in energy and water cycles by regulating the interaction of the land surface with the atmosphere ([2],[1]). The challenge of studying and quantifying many of these processes is complicated by the role spatial scale plays in driving variability, and the complex interactions among factors such as climate and land-use across spatial scales. For example, soil moisture at small spatial scales is dictated by factors such as topography, soil type, vegetation type, root structure etc., while at larger spatial scales atmospheric conditions play an important role. Moreover soil moisture variation with depth is an important parameter for understanding ecosystem water balance that only field measurements can capture and techniques such as satellite remote sensing cannot provide a complete
picture. Current satellite measurements are estimated to detect soil moisture only in the 1-2 cm depth range; whereas various processes can affect variability of soil moisture across the soil column (for example vegetation can extract moisture from deeper soil layers) ([1]).

As part of a state-wide initiative in New Hampshire to monitor ecosystems in response to climate and land-use change, an innovative, integrated statewide system of sensors was built to support research aimed at understanding the complex interactions among climate, land-use and society. The project focuses on the many services provided by ecosystems in the state: recreation and tourism, carbon sequestration, regional climate regulation, biomass for electricity generation, and pollutant removals from air, soil and water. Data from these sensors is being used to parameterize and validate a suite of climate, hydrological and ecosystem models over the extended statewide domain to predict changes in ecosystem function and understand their effects for society ([4]). The primary objective of the soil sensor network is to monitor soil temperature, moisture, respiration (soil $CO_2$ flux), and related environmental and meteorological parameters across representative land-uses. The sensing systems were deployed at seven locations across the state (summarized in Table 1). This paper describes system design, sensor and hardware selection and customization, and the challenge of developing and optimizing a power-hungry sensing system running on solar power at four of the locations.

### Table 1: Summary of seven sites chosen for the deployment of soil monitoring network.

<table>
<thead>
<tr>
<th>No.</th>
<th>Site Name</th>
<th>Land-use</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Hubbard Brook Experimental Forest (HBF)</td>
<td>Higher Elevation Pristine Northern Hardwood Forest</td>
<td>Thornton, NH</td>
</tr>
<tr>
<td>2.</td>
<td>Burley-Demeritt Farm (BDF)</td>
<td>Pasture</td>
<td>Durham, NH</td>
</tr>
<tr>
<td>3.</td>
<td>Thompson Farm (THF)</td>
<td>Uneven Aged Mixed Forest and Pasture</td>
<td>Durham, NH</td>
</tr>
<tr>
<td>4.</td>
<td>Dowst-Cate Town Forest (DCF)</td>
<td>Mixed forest with ongoing logging operations</td>
<td>Deerfield, NH</td>
</tr>
<tr>
<td>5.</td>
<td>Bartlett Experimental Forest (BRT)</td>
<td>Higher Elevation Northern Hardwood Forest With a history of logging</td>
<td>Bartlett, NH</td>
</tr>
<tr>
<td>6.</td>
<td>Saddleback Mountain (SDM)</td>
<td>Higher Elevation Mixed Forest with a history of clear cutting</td>
<td>Deerfield, NH</td>
</tr>
<tr>
<td>8.</td>
<td>Blue Hills near Trout Pond Brook (TPB)</td>
<td>Mixed Transitional Forest</td>
<td>Strafford, NH</td>
</tr>
</tbody>
</table>

2 Soil Monitoring

### 2.1 Soil Respiration

Soil respiration (SR) is the efflux of carbon dioxide from soils that is a result of a complex suite of below ground biological and physical processes involving plants, microorganisms, and soil constituents (e.g. minerals) ([7]). $CO_2$ efflux from soils is a major component of the global carbon budget and enhanced $CO_2$ fluxes due to environmental change may provide feedbacks to the climate system. SR is a complex process, highly sensitive
to temperature, moisture, and human intervention (e.g. land use change) among others ([6]). Continuous field measurements of \( CO_2 \) efflux are critical to understanding the underlying processes involved and how ecosystems will respond to climate change.

SR is highly variable at different time scales: sub-hourly, daily to seasonal, annual, and inter-annual. A widely used way to measure the areal rate of SR is by determining soil \( CO_2 \) efflux from dynamic chamber measurements over an area. \( CO_2 \) flux at a point is measured by placing a chamber over soil. Variation in \( CO_2 \) concentration within the headspace of the chamber is recorded and used to estimate a flux rate. Similar area-averaged measurements using multiple chambers spread over an area are used to determine areal flux and SR rates. A statistically significant number of chambers are required to gather data representative of a site, along with a robust, high temporal frequency sensing system capable of long term measurements with minimal downtime.

2.2 Soil Moisture

Soil moisture (SM, also referred to as volumetric water content) is the amount of water contained in soil. Almost all hydrological, biological or biogeochemical processes occurring in the soil column are affected by this parameter, making it an important indicator of ecosystem health ([5]). SM is usually determined by measuring a surrogate, dielectric permittivity, using principles of time-domain or frequency-domain reflectometry (TDR or FDR) ([3]). An FDR sensor consists of multiple prongs parallel to each other that are inserted into the soil. An oscillating electromagnetic wave sent to the prongs charges according to the dielectric permittivity of the soil. The stored charge that is proportional SM is measured. A TDR sensor consists of two metal prongs inserted at a certain depth in soil. The velocity of an electromagnetic wave propagated along the probe rods depends on the dielectric permittivity of soil surrounding the prongs. Increasing SM reduces the propagation velocity due to an increase in dielectric permittivity. The two-way travel time of the signal is measured and related to SM.

2.3 Ancillary Measurements

Weather conditions and other related parameters such as soil temperature play an important role in how SM and SR vary over time and space by affecting chemical reactions, nutrient turnover and microbial metabolism. We implemented the sensing system design to include the following variables: soil temperature, air temperature, precipitation, snow depth, wind speed and direction.

3 Sensor Node Requirements

3.1 Site Selection

Site selection required careful consideration of factors such as topography, vegetation, soil-type etc. Another important consideration was the ability to co-locate a water quality monitoring network. This was facilitate interdisciplinary research aimed at understanding the hydrological and biogeochemical linkages between the terrestrial and aquatic environments. Table 1 summarizes the location of each site with specific land-use characteristics highlighted, and Figure 1 highlights the location of these sites on a map. Six of the seven sites are within forested headwater catchments and in close proximity to a water quality monitoring network.
Figure 1: Conceptual diagram of sensor node configuration and (inset) map of sites where the sensing systems are located.

4 System Architecture

We provide a description and functionality of individual component that make up a sensing system node. A sensor system node consists of all associated sensing equipment at one specific location within the site.

1. The automated chamber and its related hardware.
2. The multi-channel gas sampling system
3. Compression system and automated chamber control
4. The soil moisture sensing system
5. Ancillary measurements system.
6. Datalogger, system control and telemetry

4.1 Multi-channel gas sampling

Each site consists of 6 to 8 dynamic automated chambers installed as part of a single sensing system. Each custom-built chamber unit (Fin-Landis Techniker LLC, Nottingham, NH), consists of a stainless steel frame with a collar, and an aluminum chamber lid (46 cm length and width, and 20 cm in depth) (Figure 2). The frame is inserted into the ground with the collar resting evenly on the surface. The chamber lid is hinged to the collar and is controlled by a pneumatic actuator arm which opens and shuts based on the flow of compressed air controlled by a compression system. Chamber closing creates incubation within the enclosure to enable
CO₂ efflux from the soil to be isolated from ambient atmospheric concentrations. A pump (NMP series micro diaphragm gas pump, rated for 2.5 liters/min of delivery, KNF Neuberger, Inc., Trenton, NJ) with a flow regulator (LI-COR Biosciences, Inc., Lincoln, NE) pulls the sample into an infrared gas analyzer (IRGA, Li-840A, LI-COR Biosciences, Inc., Lincoln, NE).

Each sample cycle consists of a 10 minute loop which includes a flushing period of 2 minutes to purge all existing gas in the sample lines. This is followed a four minute incubation period, initiated by chamber closure, to incubate CO₂ and transport it to the Inferred Gas Analyzer (IRGA). The sampling loop ends with another two minute flushing period of the sample line.

### 4.2 Compression System

An AC or DC powered compressor is at the heart of the compression system at each site. The AC compressor (GAST 1HAB-11T-M100X, Idex Corporation Benton Harbor, MI) can generate gage pressure of up to 100 psi (690 kPa) and is equipped with a 2 gallon (7.6 L) air tank. The DC powered compressor (250-IG, industrial grade, Viair Corporation, Irvine, CA) is equipped with a motor capable of generating up to 150 psi (1034 kPa) in gage pressure. Both have an internal pressure switch, that turns on power at 85 psi and off at 105 psi. The DC powered unit was integrated into the sensing system at solar power operated sites.

Tests on the compression system showed that it consumes 9 Amps at 100% duty cycle and that minimal use over a daily cycle can be achieved by using a smaller air tank (1 gallon, 3.78 L), while deploying additional measures for automated power control and monitoring of air pressure. As a result, an external solid relay (40 Amps, Crydom H12D4840D, Custom Sensors and Technologies, San Diego, CA) and an external pressure transducer (PX309, Omega Engineering, Inc. Stamford, CT) were added to the system to closely monitor the compression system. This was the first step in isolating the power hungry compression system, and reducing the likelihood of total system failure due to excessive power draw and resulting loss of remote communication. Avoiding such a loss is critical to operating remote sensing stations and minimize downtime in data collection. For this reason we
isolated the power hungry system components (compressor and pump), along with their associated components onto a separate solar power system that is isolated from the soil sensors, data logger, and integrated system telemetry.

### 4.3 Soil Moisture and Temperature Sensing

Each chamber location is paired with soil moisture sensors. We selected two types of sensors (5TM water content and temperature sensor, Decagon Devices., Inc. Pullman, WA; CS650 water content reflectometer, Campbell Scientific, Logan, UT), each with different physical characteristics for ease of installation at the depths selected for the study (5, 15, and 30 cm). A set of 8 to 10 sensors were tested for accurate measurements by inserting them in soil in the laboratory, testing them for accuracy and inconsistent behavior using a calibrated hand-held soil moisture sensor.

A soil pit, approximately 30 cm in width and 40 cm in depth pit, was dug next to each automated chamber (Figure 3(left)). The evacuated soil was carefully stored in order of its removal for later use as fill (Figure 3(right)). The 5TM sensor (10 cm in height, 3.2 cm width, prong height of 5 cm and a zone of influence extending 1 cm beyond the tip of the prong, and 2 cm along the side of the prong) was inserted vertically into the top layer of soil on the side closest to the automated chamber of soil until the prongs were concealed (Figure 3(a)). This allows measurement of soil moisture and temperature indicative of the layer of soil commonly known as organic or O-horizon. Most of surficial organic matter and microbial activity resides in non-decomposed form in the O-horizon. The CS650 sensors (38.5 cm long and 6.3 cm wide, with prong height of 30 cm and a zone of influence extending 4.5 cm beyond the tip, and 7.5 cm along the side of the prong) was inserted horizontally into the soil at 15 cm and 30 cm depth, in layers of mineral soil. The evacuated soil was deposited back into the pit in order of its retrieval. Test measurements on the sensors were collected for 1-2 weeks, allowing the soil to settle and minimize disturbance, and the sensors to equilibrate to their surroundings.

### 4.4 Ancillary Measurements

Each sensing system is equipped with additional sensors to provide data of relevant environmental parameters and support the safe and continued operation of the system. Sensors measuring air and chamber temperature,
precipitation and wind speed, were added to the sensing system. One air temperature probe (107-L, Campbell Scientific, Logan, UT) housed in a radiation shield (41303-5A, 6-Plate Gill Solar Radiation Shield R.M. Young and company, Traverse City, MI) was installed at each site. Each automated chamber is equipped with a temperature sensor, custom-built with a thermistor-type sensor (7002, thermistor, Campbell Scientific, Logan, UT).

A precipitation gage capable of measuring rain and frozen precipitation (52202-L30-LP30, Heated Rain and Snow Gage, R.M. Young and Company, Traverse City, MI) was added to select sites. The precipitation gage is protected from wind-induced measurement errors with a rain gage screen (260-953, Alter-type Rain Gage Wind Screen, 36 inch legs, NovAlynx Corporation, Grass Valley, CA). A wind monitor, capable of providing wind speed and direction (05103-10 Wind Monitor, R.M. Young and company, Traverse City, MI) was installed at each site.

The safe operation of a remotely operated solar-powered sensing system requires close monitoring of system power. We used two independent solar-powered battery banks to divide up system components. One battery bank and associated solar panel array was equipped to adequately power the gas sampling and compression systems. To monitor power consumption we employed an external voltage measuring device (VDIV10:1, 10-to-1 Voltage Divider Terminal Input Module, Campbell Scientific, Logan, UT) to record the battery banks voltage. Voltage measurements and pressure in the compression system (used for chamber operation) are made twice hourly, prior to and after a sampling cycle. We used the in-built voltage reading capability of the data logger to read the voltage of the smaller battery bank used to power the soil sensors, datalogger, and telemetry system.

4.5 Datalogging and Telemetry

A data logger and associated hardware is used to control the system components and receive, store and transmit data. Due to multiple sensor inputs and a complex set of data acquisition tasks, we chose an off-the-shelf data logger (CR1000, Campbell Scientific, Inc. Logan, UT) with a variety of features (16 single ended analog inputs, 2 pulse counters, 8 digital ports, 2 communication and data storage ports, data storage expandable from 4mb to 4GB, compatibility with a variety of communication protocols and hardware), and an easy-to-use but powerful language (CRBASIC) for system control and data collection.

Due to the distribution of sensing systems across the state, real-time remote data collection and system control capability is critical to the operation of the network. We reviewed several commercially available telemetry technologies including satellite, cellular phone and radio communication to determine which had the greatest ease of implementation, level of system control, and a manageable cost of installation and continued operation. Based on these factors a cellular phone based telemetry system was found to be most suited for implementation. We chose a cellular phone modem (Airlink RAVENXTV, CDMA technology, Sierra Wireless, Carlsbad, CA), that is compatible with the datalogger, with an antenna (14201, 900 MHz 9 dB, Yagi antenna, or 14221, 900 MHz 3 dB, omnidirectional antenna, Campbell Scientific, Inc., Logan, UT, for sites with weak or strong cellular signal strength respectively). We used off-the-shelf software (Loggernet, Campbell Scientific, Logan UT) for system control and data collection. The modem connects to the data logger through its RS-232 port, and at 115200 Baud provides high data transfer rates, and lag-free system control allowing tasks such as automated data collection, program initiation, upload, termination, and other system troubleshooting tasks.
5 Design Strategy

5.1 Energy Budget

Two of the seven sites had preexisting access to line power. We installed line power at a third and these systems were implemented with no power constraint with a resulting continuous 24 hours a day operation. The operation of four sites was implemented with solar power. With the remote, forested nature of the sites, considerable effort was made in developing the power supply infrastructure and in optimizing the system design to enable uninterrupted operation.

The power consumption of a sensing system was estimated at 700 mA per sampling cycle with daily demand at remote sites of approximately 12.9 Amp-hours at duty cycle of 30% (i.e. the system is operating and drawing power only 30% of the day). With a plan to add additional sensors in the future, the system required a minimum supply of power of 800 mA per sampling cycle (100% duty cycle for the time when the automated chamber measurements and soil moisture and ancillary environmental measurements are in effect). The corresponding daily demand was estimated at 13.6 Amp-hours at 30% duty cycle, but in order to account for any uncertainties in the estimate the power supply infrastructure was designed for a daily demand of 15 Amp-hours. It was determined that the bulk of power consumption was attributable to operating the compression system and performing the SR measurements. This allowed the design of the power supply system with two independent inputs, one to power the compression system and the automated chamber and the other to operate data logger, soil moisture sensors and the remaining components of the sensing system.

5.2 Solar Power

Site characteristics such as topography, vegetation cover and type heavily influence the amount of sunlight available for power generation. Typical solar power infrastructure consists of photovoltaic cells that convert sunlight to electricity, charge controllers that regulate the electricity generated, and allow a bank of batteries to be safely charged.

Based on initial testing and an estimated average sunlight of 5 hours each day we developed a base design of the system that included photovoltaic cells with a total capacity of 150 W, and a battery bank capable of providing power for up to 10 days. This design was initially implemented at each site and tested for its performance and based on the response observed specific to local conditions, additional photovoltaic cell capacity and battery back-up was added. Final implementation of solar power installation include photovoltaic cells (AltE Poly 50 W or 80 W panels, AltE Store, Boxborough, MA) with a total capacity ranging from 150 W to 210 W, solar charge controllers (SG-4 Sunguard 4.5 Amp 12 Volt, or SunKeeper SK-12 12A, 12V PWM Charge Controllers, Morningstar Corporation, Newtown, PA) and batteries (Xtreme, Marine Deep Cycle, 125 Amp-hours, Batteries Plus, Hartland, WI ) with two batteries connected in parallel powering the datalogger and the soil moisture sensing system and five or six batteries connected in a similar way to power the compression and automated chamber control system. The installation of the photovoltaic panels was done selectively on posts, trees, or in one case a custom built tower in close proximity to the sensing system. The battery banks and charge controllers along with the system control and telemetry equipment were housed in an off-the-shelf shed (GS3000, 1.2 m³ volume, Suncast Corporation, Batavia, IL).

5.3 System Control

Code written in the CRBASIC programming language (Campbell Scientific Inc., Logan, UT) provides control of the individual tasks of the sensing system. A typical cycle of operations at a remote solar-powered site begins
with the data logger ensuring that the battery bank voltages exceed the voltage of safe operation (11.5V), and then proceeds to generate a random number to select a chamber for operation. Tasks before the operation of the chambers include the measurement of all soil temperature and moisture, air temperature and wind speed sensors. The system then checks the pressure level in the compression system and powers the compressor if it is below 80 PSI. Power supply to the compressor is terminated after two minutes or earlier if the compressor pressure reaches 105 PSI, and then the system proceeds to perform automated chamber control tasks. The sampling pump is turned on simultaneously with the relay controller activating the sample lines according to the chamber selected. The pump flushes the line for 2 minutes prior to the start of sampling cycle. After which chamber operation commences with the initiation of the IRGA to measure \( CO_2 \) concentrations every 3 seconds. The chamber lid is closed for 4 minutes after which the chamber lid is opened and the system lines are flushed for a further 2 minutes. \( CO_2 \) concentrations are measured and recorded for the 10 minute cycle, which once complete directs the system to go into a low power state and wait for the next cycle to commence.

6 Current Data

Sensing systems at select sites began operation in 2012, and over a period of 12 months the remaining sites were brought to operational capability for core and most ancillary measurements. Following the initial deployment we continued expansion of the sensing systems to include elements such as winter measurement of soil \( CO_2 \) efflux. While upgrading the systems they continued to operate and collect data with only minimal down time while being enhanced. An example of data collected is provided here to reveal the capability of such sensing systems.

Figure 4 provides a comparison of a year-long time series of soil moisture present in soil (up to a depth of 30 cm) between two sites. Volumetric water content measurements and in-situ soil properties (bulk density and porosity) were used to estimate the area-averaged volume of moisture available at a forested (SBM) and pasture site (BDF). There is more available moisture at the pasture site than the forested site. This can be explained by a combination of soil type and vegetation type differences. The pasture with its lack of large plants has lower water demand (evapotranspiration, ET). The presence of tree roots at the forested sites increases the effective porosity of soil that allows more water to infiltrate to deeper layers of soil and decrease water availability in the shallower layers of soil. During dry periods, a higher level of ET increases water demand at the forested site relative to the pasture site. This provides a close look at moisture drawdown during prolonged dry periods. Such data in combination with the knowledge of vegetation type can be used to determine the effects of prolonged and/or frequent dry periods on the health and productivity of forests.

7 Summary and Conclusions

We provided a detailed examination of the development of a soil processes monitoring network. The network was installed across seven sites representative of different land-uses in the state of New Hampshire. Each sensing system was designed to overcome the challenges posed by site topography, vegetation type and remote location along with excessive power requirements of the system components. This resulted in the development of a robust and optimized network of sensors built to provide uninterrupted data and help increase our understanding of the environment around us.
Figure 4: Comparison of area-averaged water available in the top 30 cm of soil between a predominantly forested site and a pasture dominant site.

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References


