

# Soil Sensor Technology: Life within a Pixel

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*Soil organisms undertake every major ecosystem process, from primary production to decomposition to carbon sequestration, and those processes they catalyze have a bearing on the management of issues from agriculture to global climate change. Nonetheless, until recently, research to measure the dynamics of microscopic organisms living belowground has largely been limited to infrequent field sampling and laboratory extrapolation. Now, however, new sensor technologies can measure and monitor soil organisms and processes at rapid and continuous temporal scales. In this article, we describe these technologies and how they can be arrayed for an integrated view of soil dynamics.*

*Keywords: sensors, soils, minirhizotron, carbon dioxide, nitrate*

**S**oil organisms are the catalysts that link elemental exchange among the lithosphere, biosphere, and atmosphere. Understanding the rates of these exchanges, and the sequestration of elements within any pool, is becoming increasingly crucial to understanding soil processes and to sustainable management of local processes that are linked to the global climate. Indeed, scaling may be the single most difficult task in the study of soil ecological processes. The nutrient transformations that take place on the surfaces of soil particles, roots, and soil microbes must be defined and scaled up for managing soil nutrient and energy transformation at the ecosystem level.

The greatest challenges for predicting soil processes are learning what to measure and how frequently, and organizing individual measurements into units that correspond to a remote-sensing pixel of information. Today, pixels at scales of meters to kilometers provide composite estimates of the effects of complex soil processes, but these composites are blind to the small-scale processes that contribute to larger-scale phenomena. To fully understand these phenomena, we need to be able to measure soil processes *in situ* to determine which organisms participate and, simultaneously, to aggregate measurements in spatially and temporally meaningful ways.

A key driver of biogeochemical processes and the most readily measured soil parameter is the energy stored in carbon (C) compounds. Soil C is derived largely from plant photosynthesis and allocated to the soil either directly from plant roots or from leaf litter and decomposition. The kinetics of soil processes have been estimated in terms of respiration rates, which depend on temperature, water, and a number of other variables that vary at microscopic scales. To address these challenges of scale, we implemented a networked array of sensors designed

to measure small-scale soil dynamics and correlate these spatially and temporally with larger-scale measurements.

Describing the respiration process is relatively simple. Glucose ( $C_6H_{12}O_6$ ) is oxidized and broken down to carbon dioxide ( $CO_2$ ) and water ( $H_2O$ ), releasing ATP (adenosine triphosphate, or energy):  $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + ATP$ ; measuring  $CO_2$  fluxes in the laboratory for a cell or an organism is relatively straightforward. Unfortunately, a vast number of organisms and processes (in addition to respiration) contribute to gains and losses of C in soil. Much of the difficulty with measuring soil respiration is because of the variation in production and diffusion of  $CO_2$  in the soil profile (Hirano et al. 2003, Jassal et al. 2005). Any soil respiration measurement taken at one point in time and space may have little relationship to one taken at the next moment or at a nearby location (Belnap et al. 2003). However, because of

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the complexity of this problem and limiting technologies, most studies have been forced to assume spatial and temporal homogeneity.

General CO<sub>2</sub> models are often correct in terms of physical and biogeochemical processes, and the parameters that determine their outputs, but these attributes are usually assumed to be independent of the scale at which the model is used. A common assumption is that soil respiration can be predicted using abiotic variables, including temperature, precipitation, and clay content (e.g., using models such as DAYCENT; Parton et al. 1998). However, soil respiration is a result of complex interactions among the biotic, chemical, and physical constituents within very small regions of soil, which cause the observed variability of soil respiration (Stoyan et al. 2000, Davidson et al. 2006). Thus, because of spatial and temporal variation, regional estimates could easily be off by an order of magnitude or more. Eddy-covariance techniques can be employed to measure CO<sub>2</sub> fluxes from the canopy boundary layer to the atmosphere. This approach measures CO<sub>2</sub> along a concentration gradient between the atmosphere and the canopy at frequent (10 to 20 times per second) intervals, coupled with vertical wind speeds to integrate turbulence. However, this technique integrates a large footprint (up to several hectares) that is dependent on the height of measurement and the canopy structure.

The variation of CO<sub>2</sub> flux within the understory due to any single parameter such as temperature or water potential ( $\psi$ ) can vary two- to fourfold (Baldocchi et al. 2000). Q<sub>10</sub> ratios (the respiration rate at temperature  $t + 10$  divided by the rate at temperature  $t$  [in degrees Celsius]) are used widely to assess microbial or root respiration of individual entities, such as root tips (e.g., Burton et al. 2002), but values can vary from tip to tip depending on water and nitrogen (N). When Burton and colleagues (2002) evaluated respiration at sites across the North American continent, the range of Q<sub>10</sub> values for mycorrhizal root-tip respiration varied from 2.4 to 3.1. Root respiration *in vivo* became more predictable when the N concentration of individual tips was integrated into the model. However, because the tip included mycorrhizal fungi, which made up as much as 25 percent of the mass and 40 percent of the N, relative contributions become another question (Allen et al. 2002). In addition, root and soil respiration *in situ* were highly variable, especially when the systems were subject to drought, as with the Georgia oaks and New Mexico pinyon and juniper (Burton et al. 2002).

Water regulates respiration and soil CO<sub>2</sub> both directly and indirectly: directly, in that root and microbial growth require water (but the rates decline as water content exceeds a threshold at which oxygen [O<sub>2</sub>] becomes limiting); and indirectly, in that as soil water content increases, it fills pore space and reduces CO<sub>2</sub> amounts and diffusivity in the soil. Although water entering the soil system is generally measured at a single point and reported as monthly precipitation, snow and rainfall can be highly variable over short distances, resulting in a complex spatial pattern of soil moisture distribution. Following precipitation, water moves chaotically

downward through the soil profile through soil pores and along routes formed by earthworms and decayed roots (Jury et al. 2003, Wang et al. 2003a, 2003b), and live roots and mycorrhizal hyphae move water horizontally (Dawson 1993, Ryel et al. 2002, Allen 2007). Nonsaturating precipitation leads to spatial and temporal complexity in nutrient pulses (Belnap et al. 2003, Ivans et al. 2003) and absorbs some of the gaseous O<sub>2</sub> and CO<sub>2</sub>. Subsequent soil drying patterns beneath complex canopies are driven by further spatial variation in solar radiation (e.g., Martens et al. 2000). All of these small-scale moisture-driven processes result in complex temporal and spatial variations that influence soil respiration and CO<sub>2</sub> production (Davidson et al. 1998).

Production and turnover of roots and microbes are highly variable; lab observations and field minirhizotrons showed that absorbing networks of arbuscular mycorrhizae (AM) are produced and disappear within about a week (Friese and Allen 1991, Allen et al. 2003, Staddon et al. 2003). Ectomycorrhizae (EM) tips have life spans that vary from a few days to years, depending on N concentrations, fungal species, and the environment (Majdi et al. 2001, Allen et al. 2003, Ruess et al. 2003, Treseder et al. 2004). Rhizomorphs, structures containing a mass of intertwined hyphae, can survive for several months and persist through a growing season (Treseder et al. 2005). Many nodules formed between host plants and N-fixing bacteria persist only a matter of days, but some can also be perennial (Nygren and Ramirez 1995, Nygren et al. 2000). Turnover of severed nodules occurs within three to five days, depending on moisture and herbivory. Although on the basis of lab studies, the life spans of single bacterial colonies and hyphae are presumed to be short, there are few real data to test this idea. Allen (1993) reported that microbial biomass doubled and then dropped by 75 percent within two days after a watering event, and that after seven days, no differences between watered and unwatered treatments existed.

Spatial variation is as great as temporal variation, but it is rarely addressed. Measuring points as close as 2 centimeters (cm), Allen and MacMahon (1985) found fungal distribution patterns differed with soil C and nutrient composition, which indicated different functional time-space processes. In a maize field, tillage dictated the primary scale of distribution in process and species composition (Robertson and Freckman 1995). However, in a wildland ecosystem, species composition and functional units varied across small but distinctive spatial patches (Klironomos et al. 1999). Just as important, each process, such as nutrient uptake by mycorrhizae and ammonification, scaled differently. Unfortunately, all of these studies were based on destructive sampling, which does not allow for repeatable measurement through time. Thus, although spatial structure can be characterized instantaneously, simultaneous measurement of space and time, and the association of activity and composition changes with changes to soil environments, has remained impossible (Ettema and Wardle 2002). Despite our best efforts, we are still unable to capture complex, real-time responses of respiration to organism activity and those caused by fluctuations in physical

conditions (precipitation, temperature) or biological conditions (animal grazing and bioturbation).

### Sensor technologies

Scientists are developing new technologies that use smaller, less expensive, and more robust sensors for abiotic conditions in difficult-to-measure environments. A critical advantage in using these technologies is that spatially and temporally dense measurements can be taken to describe a phenomenon at a point, and to scale up to a region of interest. Below we describe a number of probes, image systems, and integrated components that make up a soil-sensing unit (box 1). In our test bed, all sensors and observation systems are deployed along a ridge at the San Jacinto James Reserve, a Natural Reserve System field station of the University of California ([www.jamesreserve.edu](http://www.jamesreserve.edu)), a mixed-conifer forest in southern Cali-

#### Box 1. Arrayed soil environmental units placed at the James Reserve.

Associated with each minirhizotron tube is a suite of environmental probes for soil moisture, soil temperature, and carbon dioxide (CO<sub>2</sub>), placed at three depths (2, 8, and 16 centimeters). This array of sensors constitutes a node for our network array. We recognize that for the most of the sensors, there are alternative vendors and several individually constructed units.

Sensors needed for each node:

- Vaisala Carbocap CO<sub>2</sub> probes 3
- Vaisala Carbocap transmitters 3
- Soil moisture ECHO probes 3
- Soil temperature probes, 12 bit 3
- Photosynthetic active radiation sensor 1
- Air temperature/relative humidity sensor 1

Equipment needed for each node:

- 12-bit, 4-20 mA input adapters for recording CO<sub>2</sub> values in data logger 3
- HOBO weather station model H21-001 with the capacity for up to 15 channels for sensors 1
- Solar radiation shield (for relative humidity/temperature sensor) 1
- Photosynthetic active radiation sensor bracket 1

Hardware used for each node:

- Mounting pole for data logger and sensors
- Weatherproof box for CO<sub>2</sub> transmitters (Pelican box)
- PVC pipes for CO<sub>2</sub> probes
- Gore-Tex fabric to protect CO<sub>2</sub> probes
- Cables for electrical connections

fornia. This ridge is especially suitable for testing arrays of these technologies because there is a wide spatial and temporal range in temperature, moisture, canopy coverage, and litter depths. However, the soils are relatively uniform and the bedrock shallow (figure 1).

**Respiration.** Soil CO<sub>2</sub> can be monitored both vertically and horizontally using nondispersive infrared CO<sub>2</sub> sensors buried in the soil (Hirano et al. 2003, Tang et al. 2003, Jassal et al. 2005), and linked together in a wireless sensor network. Calculating CO<sub>2</sub> flux couples the observed CO<sub>2</sub> gradients with additional information on soil texture, porosity to determine tortuosity, moisture content to determine atmospheric pore space, and temperature to assess soil diffusivity (Moldrup et al. 2003, Tang et al. 2005a). The exchange between soil and the atmosphere requires local measurement of atmospheric temperature, humidity, and barometric pressure. To supplement and calibrate data from buried sensors, CO<sub>2</sub> efflux can be measured at the soil surface with soil respiration chambers connected to an infrared gas analyzer.

**Water.** The technology for *in situ* measurement of soil moisture ( $\theta$ ) has improved rapidly over the past two decades for sensors using time domain reflectometry. A coaxial cable is placed in the soil and electromagnetic pulses are sent down the cable. The strength of the reflected signal is related to the soil moisture. Frequency domain reflectometry uses a multi-vibrator for continuous monitoring; use of this technology in particular is growing, as the cost of individual sensors has fallen significantly. In addition to water-content sensors, robust dewpoint potentiometers are available; these devices can produce soil moisture retention curves for specific soil horizons.



**Figure 1.** The soil array unit at the James Reserve. Shown are tubes for minirhizotron access, soil carbon dioxide (CO<sub>2</sub>), moisture, and temperature sensors, which are coupled to a HOBO meteorological station. CO<sub>2</sub> fluxes can be calculated using gradients in CO<sub>2</sub> coupled to the atmospheric conditions with models such as Moldrup and colleagues' (2003) or Tang and colleagues' (2005a). Photograph: Rodrigo Vargas.

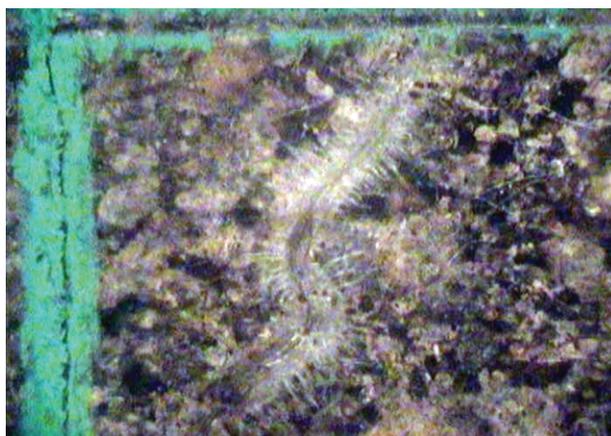
**Nitrogen.** Nitrate ( $\text{NO}_3^-$ ) and ammonium ( $\text{NH}_4^+$ ) microsensors deployment will fully characterize the spatial and temporal fluctuations of nitrogen species gradients; data collection began in August 2007. Commercial sensors for  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ , and other ionic species are relatively large (on the scale of centimeters) and expensive. However, we have produced a prototype  $\text{NO}_3^-$  ion-selective electrode (ISE) on 7-micrometer-diameter graphite carbon fibers mimicking the form factor of natural root and pore structures (Bendikov et al. 2005) by polymerizing pyrrole onto the fibers in a  $\text{NO}_3^-$  solution (Hutchins and Bachas 1995). Calibration tests comparing the microsensors response with that of commercial macroscopic sensors have demonstrated that the microsensors are equally sensitive, providing piecewise log-linear responses to a minimum detectable  $\text{NO}_3^-$  concentration of about  $10^{-5}$  molar (M) (0.5 parts per million) (Bendikov and Harmon 2005). At this stage, the nitrogen sensors are useful for short-term campaigns, and they should improve as new coating materials are developed.

Together, these sensors allow for the simultaneous *in situ* measurement of parameters critical to calculating  $\text{CO}_2$  concentrations and the processes that regulate fluxes. One remaining challenge, however, is to develop an integrated wireless technology that organizes arrays of these sensors and couples their output with  $\text{CO}_2$  emission data from soil chamber and understory eddy-covariance techniques.

### Imaging: Minirhizotron and automated microscope systems

Observing the spatial and temporal dynamics of rhizosphere organisms is a crucial step in understanding soil biota. Direct observations are possible with “minirhizotron” cameras, which provide good resolution of roots, but often only marginal resolution of mycorrhizal fungi and other soil organisms. We use camera systems and software to track sequential changes in space and time of images taken within the rhizosphere. The cameras, which are equipped with their own light sources, are inserted into transparent tubes permanently installed in the soil. Lines of 9-millimeter (mm)  $\times$  12-mm frames have been engraved into the long axis of each tube, and an image of each frame is recorded onto videotape or a laptop computer. The cameras can zoom in to fields as small as 2.25 mm  $\times$  3.0 mm—roughly 100 $\times$  magnification—allowing for observation of fine roots, fungal hyphae, and soil fauna (figure 2). We view these images in the lab and count the number of roots, rhizomorphs (Treseder et al. 2005), and mycorrhizal root tips within each frame (e.g., Crocker et al. 2003). Unfortunately, image collection and manual digitizing are still time and labor intensive (Hendrick and Pregitzer 1996).

We recently began to replace our minirhizotron tubes with a robotic automated minirhizotron (AMR) system that is completely sealed within buried tubes and communicates data and instructions through an embedded wireless network (figure 3). To assess mycorrhizal activity, fungal dynamics, and other soil organisms, we integrated a USB-port



**Figure 2.** Image of a live root, root hairs, and arbuscular mycorrhizal fungal hyphae radiating from infection points, taken with the Bartz minirhizotron image set at the highest level of resolution. The image was taken in August 2005, when soil moisture was less than  $-5$  megapascals. Roots and fungal hyphae were observed changing daily, probably using hydraulically lifted water (see Querejeta et al. 2003, 2007). Image: Michael Stoeltze and Michael Allen.



**Figure 3.** Robotic automated minirhizotron camera system using a ProScope USB-port microscope placed on mechanical rods moving within clear glass tubing. The controls for movement are connected to a server using a wireless connection. Photograph: Michael Taggart.

microscope (ProScope USB-port microscope using a 100 $\times$  lens), which provides higher resolution and better images than can be obtained from the current minirhizotrons (figure 4). Having multiple AMR cameras that respond to remote commands or environmental triggers (e.g., rainfall) will allow simultaneous data collection at multiple points in space and time.

There are thousands of unanalyzed minirhizotron images throughout the research community, and automated image acquisition will add even more. There is, therefore, a need to develop automated software to analyze images of roots and fungal hyphae. Our initial foray into automation was to perform scale-space analysis to identify linear structures in the images (Lindeberg 1998), and then to program a classifier



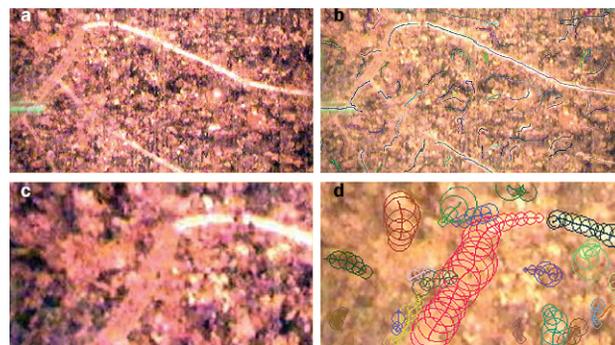
**Figure 4.** An in situ root, soil particles, and arbuscular mycorrhizae hyphae from ProScope USB-port microscope, using a 100 $\times$  lens. Image: Michael Allen.

(a support vector machine; Cortes and Vapnik 1995) to discriminate between roots, fungal hyphae, and soil (figure 5). We also experimented with simple models of temporal changes by registering adjacent images and eliminating regions with insignificant changes. More accurate and flexible deformation models must be developed, along with temporal models that can account for uneven temporal sampling and large-scale changes.

### Array organization

To test and implement these new tools for studying soil processes at varying spatial and temporal scales, we have developed a test system at a field installation at the James Reserve. This location is the habitat applications test bed for the Center for Embedded Networked Sensing (CENS; [www.cens.ucla.edu](http://www.cens.ucla.edu)) and Networked Infomechanical Systems (NIMS). CENS focuses on developing long-lived, self-configuring embedded network sensing systems. The mechanics of data acquisition and transfer are described by Hamilton and colleagues (2007). Within and surrounding the soil transect network are a cable-based mobile network, a microclimate monitoring system, and sound and camera systems to observe wildlife such as birds (Hamilton et al. 2007). NIMS is developing coordinated mobility of sensors that will allow direct determination of sensing uncertainty. This gives the sensor system the capability to assess its own performance. Specifically, NIMS exploits both fixed and mobile nodes to actively seek areas of reduced sensor coverage and map the resulting uncertainty (Hamilton et al. 2007).

We installed an array of 15 minirhizotron tubes in multiple local clusters directly aligned with a prototype NIMS system. Subarrays of three tubes each form five 2.1-meter (m) transects perpendicular to the long axis and three parallel 85-m transects. To test the array's ability to detect the scales of variation for different measurements, the distances between the imaging tubes were designed to follow a "scale-free" distribution. Described by intervals of the function  $f(x) = ax^b$ , the smallest distance between two minirhizotron tubes is 0.4 m, the next smallest is 1.7 m, and the third and fourth distances



**Figure 5.** Software under development for automated interpretation and quantification of minirhizotron images. (a) Nine-millimeter (mm) by 12-mm minirhizotron image containing a root with two branches. (b) Detected roots obtained by first searching for ridges and then classifying candidate ridges as roots using a support vector machine trained on hand-labeled data. (c) Digitally enlarged portion of the top left image (approximately 3 mm<sup>2</sup>). (d) Ridges detected; the sizes of the circles correspond to the scale (width) of the ridge, which can vary continuously along the extent of the ridge. (See [www.cens.ucla.edu/Research](http://www.cens.ucla.edu/Research).) Images: Michael Allen and Brian Fulkerson.

are 7.2 m and 30.8 m. The values of  $a$  and  $b$  were adjusted to fit the sensor distribution within the dimensions of the NIMS transect. Hypothetically, such a scaling scheme should minimize any built-in spatial bias. By identifying discontinuities in the distributions of variance in the data we collect, we expect to identify meaningful measurement scales.

In association with each minirhizotron tube, a suite of environmental probes ( $\text{CO}_2$ , temperature,  $\theta$ ,  $\psi$ , and  $\text{NO}_3^-$ ) is installed at three depths in the soil (2, 8, and 16 cm), constituting a soil-sensing unit or "node." At each node, the above-ground installation includes sensors for temperature, humidity, barometric pressure, and photosynthetically active radiation. The field transect is wired for power from photovoltaic panels, and transmitter nodes in a wireless network are in place. Nearby soil samples are collected routinely for determination of soil chemistry and for morphotyping and molecular identification of mycorrhizal fungi.

Our initial results indicate that the spatial and temporal variation can be as great across relatively small distances (within a satellite image pixel) as variation that occurs among biomes. Soil respiration values change in as little as 15-minute intervals and across distances of 50 cm to a few meters (figure 6). With this array, we can detect diurnal or seasonal pulses in soil respiration (Hirano et al. 2003, Tang et al. 2005b), but these occur only in certain locations. Tang and colleagues (2005a) studied a system with primarily mineral soil, where more than 50 percent of the respiration was probably derived from roots and mycorrhizal fungi during the growing season; thus, respiration should be very responsive to plant and mycorrhizal fungal respiration. At locations in the interspace with no litter layer (e.g., node 4, figure 6), soil

respiration shows a diurnal pattern similar to those found by Tang and colleagues (2005a). Alternatively, where there is a deep litter layer, no diurnal pattern was observed (e.g., node 1, figure 6).

Just as important as static sensor information, imagery can be coupled temporally and spatially with sensor data (figure 7). By integrating counts of roots, mycorrhizal tips,

rhizomorphs, and hyphae with information such as the integral of daily respiration, we can visualize the dynamics occurring within and among points. We are limited at this stage by the manual imaging of the minirhizotron tubes and analysis, but coupling new image-processing techniques (figure 5) with the new AMR should allow us to collect data sets that reveal unexpected patterns.

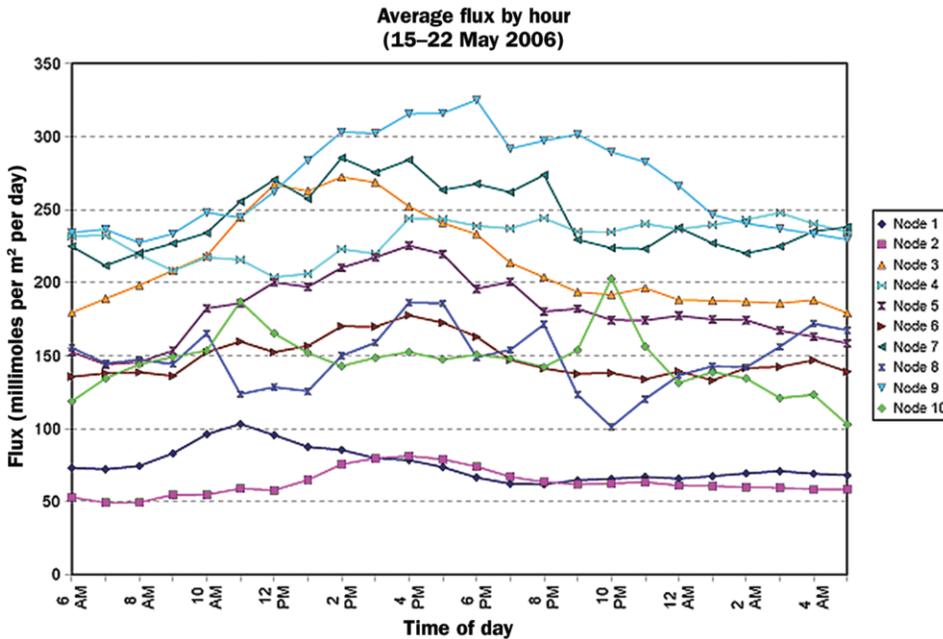


Figure 6. Variation in soil respiration across the belt transect established at the James Reserve. Nodes indicate the spatial location of a sampling unit, and are as close as 50 centimeters, and as distant as 85 meters.

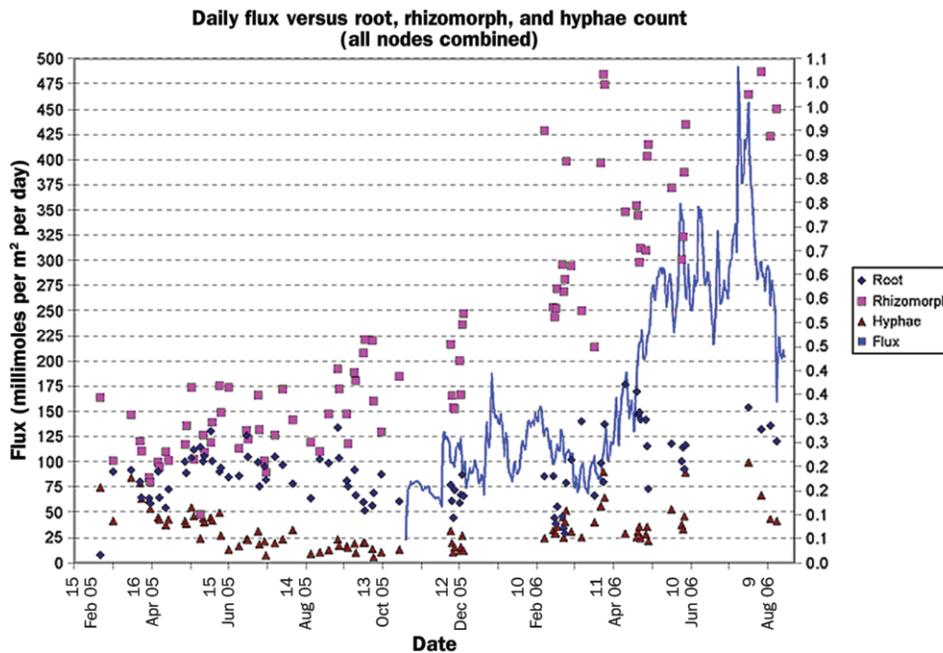


Figure 7. Integrating sensor data with root and mycorrhizal activity counts. Shown is the respiration (flux) coupled with the counts (number per frame) of roots, rhizomorphs, and coarse hyphae. The measurements are daily from March 2005 through August 2006.

### Generating new discoveries

Although sensor networks are at an early stage (see Porter et al. 2005, Collins et al. 2006), we have been able to expand on interesting observations made previously by colleagues. Among them are the following.

Mycorrhizal fungal hyphal expansion was observed at a few locations even during periods of extreme drought (in August 2005, figure 2) in the surface soils. Both EM rhizomorphs and AM hyphal networks were observed growing when soil water was less than 2 percent ( $\psi < -5$  megapascals). Respiration was measurable at these locations, but not nearby. Our preliminary data on the basis of soil moisture fluctuations suggest that this activity is from water hydraulically lifted from deeper soil layers by a few large trees (Querejeta et al. 2003, 2007).

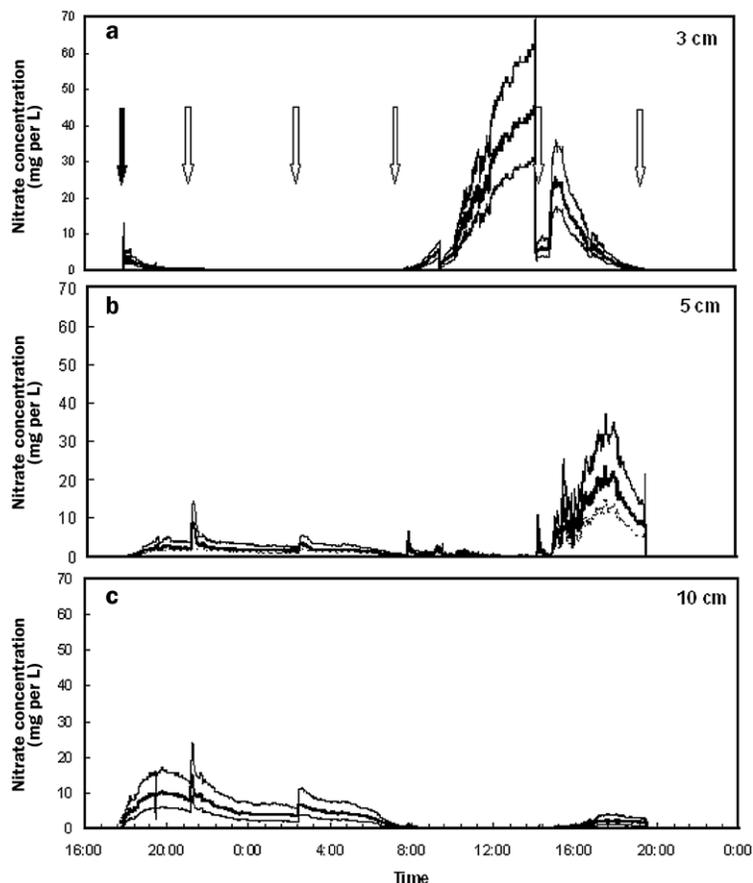
In some cases, the groups of organisms that one would predict to be responsible for the most respiration play only minor roles, whereas others are relatively more responsive. During the dry summer period of 2005 and into the winter of 2005–2006, root and fungal activity remained relatively constant, as did respiration. Beginning in March 2006, snowmelt moistened soils. With warming temperatures, respiration began to rapidly increase (figure 7), indicating more metabolic activity (higher turnover or higher maintenance respiration) instead of new growth, because there were few changes in the numbers of roots across the 15 minirhizotron tubes. From March to April, however, there was a rapid increase in fungal rhizomorphs and myc-

orrhizal root tips associated with small precipitation events and increasing soil temperature. One of our soil sensor arrays, located in the plant interspace of the transect, was much more highly variable, with few consistent trends (figure 6). In all cases, it was the rhizomorph numbers that dramatically rose, suggesting a major change in the acquisition of nutrients released from litter or from decomposition at the surface, coupled with greater allocation of plant C to the mycorrhizal fungi (figure 7). Further work on the isotopic composition of the respired  $\text{CO}_2$  should identify the source of this respired C.

*In situ* sensing of nitrogen species is less advanced than that for soil moisture and respiration, but our early results are promising in this area. To test the current technology, we installed nitrate ISEs (Sentek Directlon, United Kingdom) at multiple soil depths (3, 5, and 10 cm) at an experimental irrigation site in Palmdale, California, along with soil moisture (EC-5, Decagon Devices) and temperature sensors (TMC-HD, Onset Computer Corporation). We applied a 0.001-M nitrate solution (62 milligrams per liter) to the soil surface and used a circular irrigation pivot to apply water to the site on roughly a six-hour cycle. Our assumption here was that we would observe nitrate pulse sequentially with depth if the sensors remained viable throughout multiple days.

The plots in figure 8 demonstrate that we have the ability to track nitrate pulses in the soil horizon, at least for short periods of time. Although there is clearly some early transport of the nitrate immediately following its application to the surface, the main nitrate pulse arrives at the 3-cm sensor after three irrigation events (roughly 14 hours after the start of the experiment). The pulse then progresses to the 5-cm sensor one irrigation event (roughly 8 hours) later. The arrival of the pulse at the deep sensor is not apparent because the experiment was terminated in order to extract and test the sensor calibration. The postexperimental calibration agreed well with the preexperimental calibration, suggesting that these sensors are viable for at least 36 hours. Such durations can be useful for short-term sampling campaigns; however, longer duty cycles are needed if we are to incorporate these sensors into long-term investigations.

We have shown that sensors can be placed in areas subject to violent weather or other conditions that preclude taking measurements by hand. For example, we were able to monitor soil  $\text{CO}_2$  dynamics in the Yucatán Peninsula during Hurricane Wilma in October 2005. Wilma was the strongest Atlantic hurricane ever recorded when it reached the peninsula at Cozumel, with winds exceeding 200 kilometers per hour and barometric pressure the lowest ever recorded in the Atlantic basin (882 millibars). At our field station at the El Eden Ecological Reserve, we observed the changes in barometric pressure, photosynthetic active radiation, air and soil temperature, and soil moisture during the hurricane, and  $\text{CO}_2$

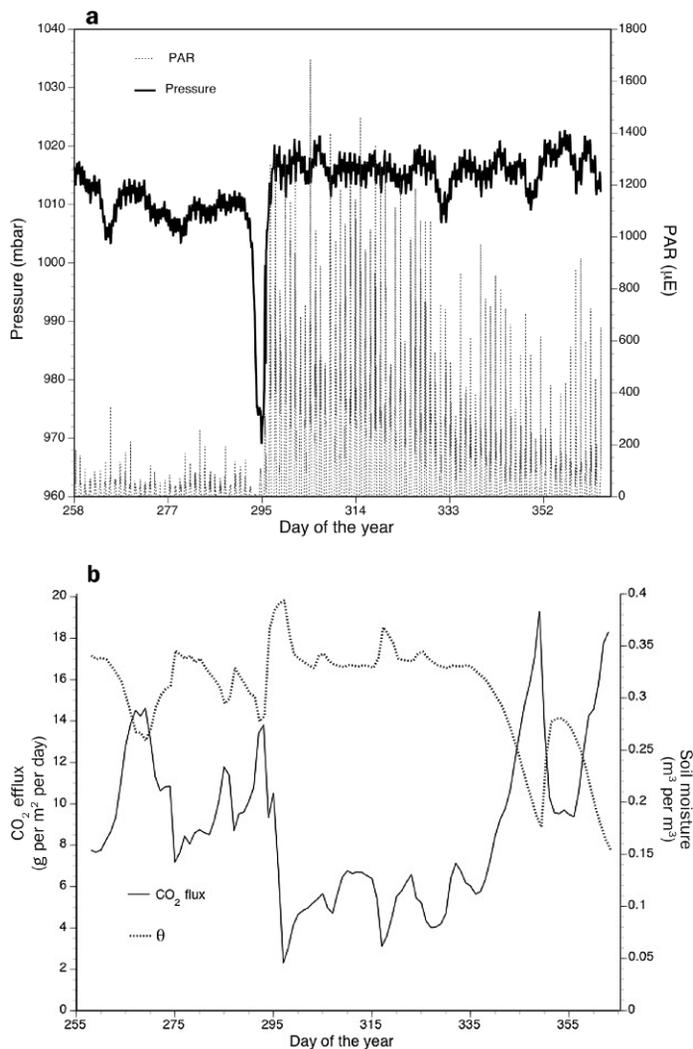


**Figure 8.** Commercial nitrate sensor response as a function of depth in Palmdale, California, desert soils following a controlled release of 0.001 molar (62 milligrams per liter) nitrate solution (black arrow) and periodic irrigation events (white arrows); average sensor response (solid line) surrounded by 95 percent confidence bands (dashed lines).

until the hurricane hit and the power supply failed (figure 9); when the power was restored, all sensors were operational. The coupled sensor data and model show an unexpected pattern: We anticipated that a drop in barometric pressure would degas the soil, resulting in an initial increase, followed by a decrease, in apparent respiration. However, soil moisture saturated before the hurricane eye arrived and appears to have reduced respiration, either because of low  $\text{O}_2$  tension or simply because a loss of air-filled pore space decreased  $\text{CO}_2$  diffusivity. Was the soil  $\text{CO}_2$  leached as dissolved inorganic C, and if so, is this of a magnitude significant to these ecosystems?

## Conclusion

Soil microbes act at scales down to tens of microns. As we scale up to cubic meters, the measurements critical to ecosystem modeling, the variation scales accordingly. Most microbial measurements to date, such as biomass or hyphal length, have been single time-point measurements. Using *in situ* camera systems and sensors, we are beginning to capture not just point measurement means but also variances and dynamics. By measuring and characterizing small spatiotemporal



**Figure 9.** (a) Barometric pressure (in millibars) and photosynthetic active radiation (PAR) before and after Hurricane Wilma and (b) daily integrated carbon dioxide ( $\text{CO}_2$ ) flux versus soil moisture ( $\theta$ ) through Hurricane Wilma in the Yucatán Peninsula. Note the drop in barometric pressure and the rise in PAR as a result of denudation of leaves in the forest after the eye of the hurricane passed on day 295 of the year 2005. The effect of the barometric pressure drop on soil degassing was far less important than we had predicted, most likely because the soil matrix was completely saturated before the hurricane eye passed over the site. Respiration dropped dramatically in the saturated soil, probably due to a direct drop in respiration because of low  $\text{O}_2$  content and a decrease in  $\text{CO}_2$  diffusivity because of water saturation in the soil.

dynamics, we should be able to test and refine models of C and N fluxes, such as DAYCENT, that are becoming critical tools for modeling regional to global carbon dynamics. The technology is available. What is needed is to put together the various tools and to develop software capable of showing fluxes and regulators at pixel, stand, landscape levels.

Determining specific sources and sinks of  $\text{CO}_2$  has been difficult because soil processes have been treated largely as homogeneous black boxes. With the development of the tools and technology described here, we can bring soil ecology to the cutting edge for studying carbon balance processes. Because these new tools vastly expand the quantities of recordable information, they inherently present new challenges for data filtering and analysis. Our prototypes constitute the horse-and-buggy phase of applying these technologies to environmental sensing and information transfer. They are the harbingers of a new suite of methods for studying complex ecophysiological processes. Moreover, this strategy of employing state-of-the-art sensor and wireless network technology should be applicable to many types of ecological research. Wherever there is a need to understand processes that interconnect across a range of scales and ramify to produce large-scale phenomena, variations on this approach should be useful. We need only the right sensors for the job.

### Acknowledgments

We would like to thank Veronique Rorive, Chris Glover, Kuni Kitajima, Niles Hasselquist, Alisha Glass, Alysia Hamrick, Diana Hwang, Natasha Ly, Yeonjeong Park, Elias Serna, Jianwu Tang, Tracy Tennant, and Mike Wimbrow for their invaluable assistance and advice in carrying this project forward. This work has been supported by the National Science Foundation, grants EF 0410408 and DEB 0615427 (to M. F. A.), the Kearney Foundation (to R. V.), contract CRR-0120778 (to D. E.), and the University of California Natural Reserve System and Agricultural Experiment Station.

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doi:10.1641/B571008

Include this information when citing this material.