Title

New Approaches in Embedded Networked Sensing for Terrestrial Ecological Observatories

Authors
Hamilton, Michael
Graham, Eric
Rundel, Phil
et al.

Publication Date
2007-05-05

Peer reviewed

ENVIRONMENTAL ENGINEERING SCIENCE
Volume 24, Number 2, 2007

DOI: 10.1089/ees.2006.0045

New Approaches in Embedded Networked Sensing for Terrestrial Ecological Observatories

Michael P. Hamilton,[1*] Eric A. Graham,[2] Philip W. Rundel,[2,3] Michael F. Allen,[4] William Kaiser,[2,5] Mark H. Hansen,[2,6] and Deborah L. Estrin[2]

[1]James San Jacinto Mountains Reserve
University of California
Idyllwild, CA 92549-1775
[2]Center for Embedded Networked Sensing
University of California, Los Angeles
Los Angeles, CA 90095-1596
[3]Department of Ecology and Evolutionary Biology
University of California, Los Angeles
Los Angeles, CA 90095-1606
[4]Center for Conservation Biology
University of California, Riverside
Riverside, CA 92521-0334
[5]Electrical Engineering Department
University of California, Los Angeles
Los Angeles, CA 90095-1594
[6]Department of Statistics
University of California, Los Angeles
Los Angeles, CA 90095

ABSTRACT

Ecological observatories are a new class of multiuser research infrastructure designed and deployed to address a broad range of continental-scale ecological questions that until only recently were not technologically feasible. These highly networked ecological observatories, spread across the United States and featuring a diverse integration of programmable sensing capabilities and remote observational functions are expected to enable a transformation in the scope of environmental research, particularly in relation to understanding how global climate shifts and local and regional land use changes will quantitatively affect the composition, structure, and dynamics of the nation's ecosystems and services. Observing systems research focused on terrestrial ecology is one of four core research application fields of the Center for Embedded Networked Sensing, which operates an engineering and experimental test bed located at the James San Jacinto Mountains Reserve, a biological field station that is part of the University of California Nat-

*Corresponding author: James San Jacinto Mountains Reserve, University of California, Post Office Box 1775, Idyllwild, CA 92549-1775. *Phone:* 951-659-3811; *Fax:* 951-659-0553; *E-mail:* mhamilton@jamesreserve.edu

ural Reserve System. This paper describes the various experimental and deployed embedded networked sensing systems at the James Reserve, and suggests how similar systems and related infrastructure will be key to meeting the engineering and science objectives of future ecological research.

Key words: NEON; environmental observatories; wireless sensor networks; cyberinfrastructure; informatics; robotics; ecology; microclimate

INTRODUCTION TO ECOLOGICAL OBSERVATORIES

Understanding changes in the composition, structure, and dynamics of the nation's ecosystems and services and how these changes are likely to affect us, present complex challenges that require the coordinated measurement of a wide range of physical and biotic elements (Hamilton, 2004; Porter *et al.,* 2005). Fortunately, new generations of terrestrial and aquatic ecological observatories, building upon the successes of today's active biological and marine field stations and incorporating the newest developments in remote sensing and information management systems, are allowing scientists to conduct environmental and ecological research over a broader range of temporal and spatial scales than previously possible (Arzberger, 2004). The new generation of *ecological observatories* (EO), featuring a diverse integration of programmable sensing capabilities and remote observational functions, will enable a transformation in the scope of environmental research, particularly in relation to understanding the interrelationships between local, regional, and continental-scale patterns and long-term processes.

One of the most ambitious new EO programs at the National Science Foundation is the National Ecological Observatory Network (NEON <www.neoninc.org>). The mission of NEON is to provide the capacity to forecast future states of ecological systems for the advancement of science and the benefit of society by focusing on several key questions, or "grand challenges" (AIBS, 2003; National Science Foundation, 2000, 2003; National Research Council, 2001, 2003). Summarized these are: (1) how are ecological systems affected by changes in land use, climate, and biogeochemistry across a range of spatial and temporal scales? (2) how do changes in the availability and distribution of the nation's water supply affect ecological systems? (3) how do the patterns and movement of genes and organisms across the continent affect biodiversity, ecosystem function, and the spread of infectious diseases and invasive species? In order to quantify and forecast these changes, NEON infrastructure must advance the integration of multi-scale, spatially dense, real-time, biologically relevant observations, many of which will be automated, by utilizing embedded networked sensors and other types of networked instrumentation (Senkowski, 2005).

A core feature of ecological observatories is standardized networked instrument arrays deployed on towers, in soil, and underwater, situated at one or more of the primary climatic regions of the United States. NEON proposes to incorporate a cluster of three sites within a region, each centered in a land cover type that is urbanized, agricultural, and wild land ecosystems, respectively. Within each, there will be as many as 10 replicates of sensor networks and data acquisition systems in order to capture variability that would occur due to local site variation. The instrumented units are being engineered to provide continuous data streams that mechanistically relate to the core ecological questions and to be used for sampling key indicator organisms and processes that are most likely to be sensitive to ecological change. Instruments and data streams will be managed by a infrastructure specifically engineered to provide detailed and comprehensive "sensor-to-scientist" operation, including control and calibration of sensors and instruments, tools for data query and mining, statistical analysis tools, modeling and simulation capabilities, and scientific data visualization (Estrin *et al.,* 2003; AIBS, 2003). Data uses will range from scientific, policymaking, and educational applications, and the systems as a whole will be sufficiently modular to add additional functionality and extend the overall number of observatories as new partner agencies and organizations become involved with NEON.

During the past 4 years, the Center for Embedded Networked Sensing (CENS <http://cens.ucla.edu>), a National Science Foundation Science and Technology Center, has worked to research and develop new environmental and ecological observing systems technologies that have relevance to the technological and scientific needs of proposed ecological observatories such as NEON, CLEANER (the Collaborative Large-Scale Engineering Analysis Network for Environmental Research), and ocean observatories (CENS, 2005). An objective of the CENS terrestrial ecologists has been to address aspects of the carbon cycle through the following three long-term studies: (1) quantifying large-area plant and animal phenologic events using imagers as biological sensors, (2) quantifying the contribution by lateral movements of air to the vertical gradients of CO_2 in a complex forested environment, and (3) determining methods for measuring energy dynamics beneath vegetation canopies using either measured or estimated solar and thermal radiation values at the soil surface. Currently, the number and types of sensors and networks needed to address such questions either are already deployed and collecting data or are on the hard schedule for implementation. These focus areas address key aspects of the ecological grand challenges, and serve as technology drivers around which CENS engineers and computer scientists are able to become fully engaged.

TERRESTRIAL ECOLOGY OBSERVING SYSTEMS AT THE JAMES RESERVE

Observing systems research focused on terrestrial ecology is one of the four core research application fields of CENS. Our program is directed by faculty from the University of California campuses at Los Angeles, Riverside, and Merced, with a deployed engineering and experimental test bed located at the University of California James San Jacinto Mountains Reserve, a biological field station operated by the UC Natural Reserve System (<http://nrs.ucop.edu>). The reserve has served as the CENS terrestrial ecology observing systems (TEOS) field site since 2002, providing core infrastructure for multiple users to deploy and remotely operate experimental networked instruments and sensor arrays within undisturbed terrestrial and fresh water ecosystems (<www.jamesreserve.edu>). Located in southern California in the San Jacinto Mountains east of Los Angeles, the James Reserve is surrounded by the San Bernardino National Forest. At an elevation of 5380 ft (1640 m), the reserve straddles the intersection of several distinct ecosystems, including montane mixed conifer and oak forest, montane chaparral, wet and dry meadows, montane riparian forest, a perennial stream, and an artificial lake. A 700 acre (283 ha) watershed surrounding the 29 acre (11.75 ha) university-owned land is managed as a Federal Research Natural Area (RNA), and is available for traditional biological field research investigations. The reserve features overnight facilities, offices, and lab space, a resident staff of programmers, engineers, and biologists, wireless Internet access that stretches over most of the reserve area, and several high-speed servers.

Over the past 4 years, CENS researchers have deployed a diversity of fixed and mobile (robotic) networked instruments and sensor arrays, some of which serve the needs for engineering and software development field tests, while others support short and long-term biological investigations. Table 1 presents a matrix of our currently deployed systems, hardware and software development platforms, sensors streams and related data types, spatial and temporal coverage of the data streams, and the ecological focus of our tests. The four primary categories of networked instruments, sensornets, and cyberinfrastructure now in place at the James Reserve are described. In this paper, we do not detail the use of each of these systems; rather we provide a few selected case examples of systems and data within applications and discuss progress in developing the cyberinfrastructure to manage fielded systems, databases, and user access.

MOBILE, FIXED, AND UNTETHERED ENS SYSTEMS

Our primary long-term objective is to design, develop, deploy, support, and evaluate distributed, continuously operating within each ecosystem or habitat (*in situ*) *embedded networked sensors* (ENS) and instrumented platforms for measuring environmental, physiological, and ecological variables within diverse natural ecosystems. Additionally, we are developing and evaluating data storage and user interface systems that allow the measurement data to be used efficiently for current research projects and as a model for future observing systems that we intend to deploy. The overall approach is an iterative process of developing modular system components collaboratively with both researchers and engineers, and then building and deploying those components, testing and feeding results back to the investigators and engineers. We use what we learn in this process to improve the existing components and design new ones.

Three distinct, yet spatially overlapping classes of instrumented arrays are currently in use at the James Reserve: (1) *mobile robotic nodes* are above-ground cable-deployed networked infomechanical systems (NIMS) and below-ground automated minirhizotrons (AMR) for continuous and event-driven operation. These mobile systems vary depending on their particular development versions, but in general they are powered by Pentium-class microprocessors, motor controllers that are either direct drive or stepper type to move the sensor platform along a cable (in the case of NIMS) or along tracks in the case of the AMR; (2) *connected fixed nodes* are sensor networks supported by a buried power and communication distribution infrastructure for continuous, high data rate applications, including environmental sensors measuring microclimate, chemical sensors for both atmospheric and

Table 1. TEOS embedded networked systems and applications.

Networked instrumented arrays and systems	*Hardware and software development platforms*	*Sensor streams and data types*	*Spatial, temporal coverage*	*Ecological focus areas*
Mobile robotic nodes	Networked infomechanical systems (NIMS)	Articulated imagers, high-resolution motion JPEG Microclimate (temp, humidity, PAR) Energy flux, thermal IR scans of soil surfaces 3-D mesh laser scan of plant leaves, structures, and visible surfaces	High-resolution sensing and sampling in 3-D Rapid deployment in response to triggered events	Plant phenology, physiology, photosynthesis, and respiration Soil surface characteristics, energy flux, CO_2 flux Microclimate dynamics within and below canopy
Connected fixed nodes	Tower-based networked robotic video cameras, streaming digital audio via stereo microphones Vertical sensor array Automated minirhizotron robotic imager Soil sensor array Nest boxes CCD imagers and sensors	Articulated imagers, high-resolution motion PEG Biacoustic signatures (classify and localize sources) Microclimate above and below ground (temp, humidity, moisture, PAR, rainfall, wind) Soil water potential NO_3, CO_2 concentration Sap flow, transcription rates	Optimized location in 3-D Actuated sensing in response to triggered events Variable spatial and temporal resolution (micron to meters) Continuous, high-resolution sensing	Plant phenology, physiology, photosynthesis, and respiration Soil and root ecology, carbon flux in soils, energy budget Microclimate dynamics Avian behavior and reproductive success in nest boxes, sensing of social interactions of woodpeckers using acoustic and video
Untethered fixed nodes	CMS1 (wireless mote class sensor network) ESS2 (wireless mote class sensor network) DAS, TENET, EMISSARY, AURICLE Networked mote CMOS imagers (CYCLOPS)	Microclimate (temp, humidity, rainfall, wind) system metrics Acoustic localization Low-resolution JPEG images generating spectral signatures of biological activity, object classification	Access to non-navigable areas Scalability of deployment Variable temporal and spatial resolution (mm-m) Continuous low energy vigilance	Microclimate dynamics within a cold air drainage (CAD) Plant phenology, animal activity
Cyberinfrastructure	Data management system Geographic information systems Image analysis and classification Embedded statistics	Airborne and satellite multispectral imagery (e.g., Quickbird, MODIS) Geodatabase queries using GIS Geospatial and statistical modeling tools Data visualization tools	Database updates every 5 min to once daily 0.1–250 M^2 1–2 days (MODIS) to annually acquired digital air photo survey	Applies to all fields and studies

subsurface measurement of CO_2 and nitrate, video imagers, and acoustical sensors; and (3) *untethered fixed nodes* are battery-powered, solar-charged, wireless communicating, tiered sensor networks consisting of Crossbow motes (MPR400 8-bit AVR microcontroller) and X-Scale based Intel Stargates (PXA255 32-bit microserver platform, Santa Clara, CA), which are optimized for low-energy, long-lived operation. These systems are used primarily as a platform for environmental sensors, including microclimate and soil moisture.

All three classes of ENS systems support a common protocol of measuring standard meteorologic data, including ambient temperature, humidity, leaf wetness, rainfall, wind speed and direction, and solar radiation, usually in the spectrum of photosynthetically active radiation—that is, 400–700 nm (PAR). Additional environmental measurements from connected fixed and mobile nodes include soil temperature, soil moisture, soil water potential, atmospheric and soil CO_2, and soil NO_3. All three ENS systems support digital image acquisition, and in each case we are developing onboard processing capability for feature extraction and event detection. In addition to these generic measurements and capabilities, highly specialized instruments and algorithms have been designed to explore a range of ecological observations including acoustic signal processing of avian vocalization, source localization (sound, light intensities, pulses), 3-D surface scanning using lasers, thermal IR measurements of soils and plants, and simultaneous, real-time multi-scale analysis, modeling, and visualization of measurements across overlapping observing systems.

While each of these systems and platforms provide our team with a versatile test bed for ENS systems design, hardware engineering, and algorithm development, it has been our goal to concurrently carry out measurements that are pertinent to science objectives, particularly those suitable for addressing overarching questions germane to future ecological observatory specifications and capabilities.

ECOLOGICAL FOCUS AREAS

There is tremendous interest in the application of sensor networks for ecological research, with the promise that sensor networks will reveal what was previously unobservable (Arzberger, 2005; Estrin *et al.,* 2003; Porter *et al.,* 2003). Continuously operating, spatially extensive networked systems can vastly extend the reach of traditional field research by: (1) increasing the reliability, quality, and quantity of data by orders of magnitude; (2) generating new types of data that integrate complex processes; (3) allowing researchers to access data streams and control field instruments via the Internet; and, (4) advancing data collection, analysis, and modeling from a historically batched process to one that is continuous and in parallel with data streams. Such new processes will be interactively viewable from either the field or back in the office and are dynamically adaptive because data analysis and simulation model results can feed back into data acquisition and experimental controls.

In the following sections, we describe three cases in the use of ENS systems for specific ecological applications. Each case describes a set of scientific questions, followed by a description of the ENS systems used to address them, with examples of data sets and analyses. While these cases are in no way inclusive of the range of capabilities offered by ENS, they demonstrate key functional elements that are particularly relevant to developers of terrestrial observing systems.

Capturing microclimate variability to study nesting birds

Well before global climate change became a household word, few themes were as central to basic and applied ecological research as the relationship of microclimate to ecological patterns, processes, organism life history, and biological diversity. Microclimate is literally the environment closest to surfaces, for example, on or within soils, under rocks, or in the canopy of a tree. Individual plants and animals may disperse over broad areas, but establishment, growth, and successful reproduction depend on a particular range of environmental conditions that frequently vary nonlinearly across spatial and temporal gradients (Matlack, 1993), including structural features of terrain, vegetation boundaries, disturbances, and seasonality. For instance, we see the stand of trees that reached the right microclimate as seeds but not the tens of thousands of seeds that perished because they failed to germinate or germinated in areas outside the range of their tolerance (Baldi, 1999; Cadenasso *et al.,* 1997; Brothers, 1993).

Through their presence and activity, organisms alter their surroundings in important ways. Tree shape, physiology, and canopy structure can produce significantly different ranges of light, humidity, and temperature in one area than might occur in an adjacent open area (Chen *et al.,* 1992, 1995). In addition, burrow-nesting birds, insects, or mammals might create a further unique range of climatic values through their nest-chamber construction (Jackson *et al.,* 2002). It is important to note that organisms do not experience the average climate but a specific microclimate on a scale proportional to their size. The ecologist who relies on extrapolations from a few measurements at localities removed from the precise location of the study species risks failing to accurately measure the degree of microenvironmental variance that an organism experiences.

Our interest in microclimate variation over multiple spatial and temporal scales relates to the importance of climate as a fundamental driver for so many ecological processes. In fact, all three of the ecological grand challenges described earlier presume that climate change and microclimate shifts will influence ecological processes and patterns of biodiversity in highly complex ways. Understanding how microclimate fluctuates over geographic and ecologically diverse contexts requires that many more simultaneous measurements be made, along with corresponding assessment of responses by organisms and ecosystems. While a number of studies have quantified these relationships in a narrow context, only with the scaleable capacity for coordinated measurements using sensor networks do we now possess the unique opportunity to measure responses continuously and over increasingly wider spatial contexts leading to understanding of organism environmental limitations.

The first untethered sensor network at the James Reserve was a 10 node, 100 sensor array continuous measurement system (CMS) designed to continuously measure microclimate by placing nodes within distinct wildlife habitats utilized by native breeding birds (Szewczyk *et al.,* 2004). The CMS uses the first-generation Crossbox motes (MICA 1) and a microserver based on a Compaq iPaq handheld computer (Hewlett-Packard, Palo Alto, CA). An analog and digital sensor interface board was engineered by CENS to be attached to each mote, allowing up to eight external sensors to be interfaced. Two types of microclimate weather stations were constructed, the first a free-standing configuration that measures basic meteorologic variables (temperature, humidity, wind, rain, PAR) and a second type that incorporates internal temperature and humidity sensors within a standard blue bird nest box. External sensors attached to the nest box mounting pole measure temperature, humidity, PAR, soil moisture, and soil temperature. One time per minute, sensors measurement values are routed from a mote to its neighbor's motes via 433 MHz radios using a flooding algorithm. Each mote in turn passes its sensor measurements, as well as its neighbor's measurements, to any motes within radio range, until packets eventually reach the microserver where messages are sent back to the mote, indicating that data has been received. Data are stored on the microserver until they can be successfully handed off to a primary gateway server, where the measurements populate a mySQL database.

Approximately every 5 min, the CMS stores microclimate sensor values applies a date and time stamp for each record and records system diagnostic measurements, including mote temperature, humidity, battery voltage, message loss, message hops, and signal strength. Interruption in the data stream occurs infrequently, and in most cases the data are then temporarily stored either on the motes or in the microserver until network communication is reestablished. A Java-based applet was written by our programmers to graphically display one or more data streams as a trace graph, summarized by hours, days, weeks, or months. The CMS data management system (DMS) allows for export of data by user selectable values and date ranges, and the DMS database stores associated data, such as JPEG images from any networked video camera sensor and location metadata, as well as any ecological attribute. While the CMS is simplistic in its design, and is an early prototype in terms of its routing and energy conservation algorithms, it has proven to be a very robust system and has delivered continuous data streams with relatively few failures since May 2003.

In addition to the microclimate sensors, each nest box has a downward-pointing miniature infrared-sensitive CCD camera and a diffused, infrared LED light source. The cameras are hard-wired via direct-burial coaxial cable to a networked video server (Axis model 2400, Axis Communications AB, Lund, Sweden) located in our main server room. The video server delivers up to 10 JPEG images per second, although for archival purposes, we store one image every 15 min into the DMS. A staff biologist reviews these images, and nest box activity patterns are recorded through the nesting season. Table 2 presents an example of one of these data tables. Work is currently ongoing in the development of image-processing approaches to automatically characterize some of these activity patterns. So far the methods are reliable for certain types of activities (e.g., eggs present without an adult or adult bird present). Video content analysis techniques are becoming increasingly more important as many CENS ENS systems are now generating streaming image and acoustical data.

The modern "canary in the mine shaft": Avian studies using ENS. Birds have long been considered important indicators of fine-scale fluctuations in environmental conditions (Holmes and Sherry, 2001; McCarty, 2001; Sydeman *et al.,* 2001). Birds select nest sites (including artificial nest boxes) based on the qualities of the site and surrounding habitat. Some characteristics do not change over the timeframe of a breeding season (e.g., the number of trees within the bird's territory). However, some characteristics (e.g., box temperature) will change between the time of site selection and the time of fledging. Before it begins building a nest, the bird must assess what the conditions will be like at a future time. How is a bird able to determine the future nesting quality of a box by its conditions at the time of initial box inspection?

Table 2. Avian nest box and reproduction monitoring from 2004 breeding season.

	Nest building	*Eggs laid*	*Incubation*	*Eggs hatched*	*Days to fledging*
Nest box 8	Successful				
Duration	32 days	5 eggs	18 days	5 eggs	24 days
Start	05/02/04	06/03/04	06/03/04	06/21/04	06/21/04
End	06/03/04	06/07/04	06/21/04	06/21/04	07/15/04
Nest box 22	Successful				
Duration	13 days	5 eggs	13 days	4 eggs	23 days
Start	04/20/04	05/03/04	05/06/04	05/19/04	05/19/04
End	05/03/04	05/07/04	05/19/04	05/23/04	06/11/04
Nest box 31	Successful				
Duration	9 days	5 eggs	15 days	4 eggs	23 days
Start	05/01/04	05/10/04	05/12/04	05/27/04	05/27/04
End	05/10/04	05/14/04	05/27/04	05/28/04	06/19/04
Nest box 27	Abandoned		Nest box 47	Abandoned	
Duration	1		Duration	8	
Start	05/02/04		Start	05/21/04	
End	05/03/04		End	05/29/04	
Nest boxes 3, 14, 21, 45, 48, 54, 55 vacant					

Thirteen nest boxes were monitored using environmental sensors and digital video.

Sensors in active nest boxes can provide information about the qualities of nest boxes that influence the selection by birds, the success of their nests, the differences between species in incubation patterns and capabilities, and individual variation in incubation pattern and feeding and how this relates to fledging success.

The environmental conditions inside and outside a nest box may influence avian nesting success. A box that is always in the shade may require the parent to spend more time incubating and brooding the birds, particularly in the morning, whereas a box in full sun might overheat. If the parent is required to brood for longer periods, feeding the nestlings may be constrained, leading to a slower nestling growth rate.

Do temperature and/or humidity outside the box place constraints on parental activity during the incubation period (e.g., time spent on nest, off nest, feeding partner) or nestling period (number and frequency of feedings, time spent brooding)? How well is the parent able to maintain the internal temperature and/or humidity in spite of varying outside microclimatic conditions? How do these factors influence nesting success?

Different species are also likely to vary in their incubation abilities. A bird's mass, egg size, and other factors will alter the thermodynamics of incubation. The varying diets of other species also place energetic constraints on nestling feeding frequency. How do species differ in their incubation abilities and temperatures?

An example of how the combination of video imagery and microclimate sensors can be used to provide insight into avian nesting ecology is shown by the activity recorded in a sample nest box. In 2003, nest box 8 was occupied by violet-green swallows (*Tachycineta thalassina* [VGSW]) whose eggs hatched on June 16. The nestlings died on June 20 at approximately 15:30. We were able to determine the time of death by inspecting the archived video images and finding the time at which the nestlings stopped moving.

The CMS provides evidence that suggests the cause of death was abnormally cold weather. During the first 4 days after hatching, nest box 8 experienced normal weather. On June 8, the daytime high temperature dropped to 11°C, which was 17–23° colder than normal; also the PAR was lower than normal, indicating that potential solar heating was also low.

The naked chicks may have simply died from exposure to cold. However, the activity of the parents suggests that the nestlings died from an indirect consequence of the cold and lack of food. The imagery from nest box 8 was archived every 15 min, which allowed us to quantify the VGSW parent behavior during this weather event. Swallows are aerial foragers and depend on airborne insects for food and insects, which are more active during warm sunny weather. During the first 4 days of the nestling period, a parent began its foraging between 8:00 and 9:00, spending approximately 50% of its time in the box until evening. On June 20, however, the parent spent most of its time on the nest (until 11:30), because it was so cold that it needed to continue brooding to keep the nestlings warm or because no insects were flying. When the adult finally left the nest to forage, it rarely returned for the rest of the day. On June 16–19, the parent was rarely away from the nest for more than 25% of any 2 hour period, but on June 20 the parent spent less than 25% of the time at the nest from 13:45 to 18:00. The swallows had to spend more time foraging because of the scarcity of aerial insects and thus were unable to attend to its nestlings. The chicks died during this period, either from starvation or from exposure because the parent had to forage, precluding brooding.

While this example from nest box 8 provides only anecdotal evidence of the cause of nest failure, it illustrates the potential of the technology to quantify the often subtle influence of microclimate variability on organism survival. A full network of sensors, such as the CMS deployed in a network of 20 or more nest boxes, will allow us to detect events and will provide the tools to analyze quantitatively the factors involved in avian reproductive success in montane forests. Our next generation mote-class ENS will allow us to begin testing a larger distributed network that can be installed in all of the nearly 40 James Reserve nest boxes. CMS is scheduled to be replaced byextensible sensor system (ESS) in mid-2006. ESS supports advanced routing functionality, energy management, and systems diagnostics for enhanced reliability and increased scalability. With ESS, future deployments will provide comprehensive measurements of microclimate variables over diverse terrain conditions, spanning hundreds of hectare and delivering real-time measurements suitable for modeling the dynamics of microclimate variability, such as cold air drainage flow and, when fused with other data sources such as imagery, as a predictor of the expected plant physiologic and phenologic responses to climatic fluctuations (Badeck *et al.,* 2004).

Cameras as biological sensors to track ecosystem response

Characterization, quantification, and prediction of ecological responses to climate change are a top priority for NEON and other environmental observatories currently being planned. One class of strategic tools for assessing global vegetation responses is remote sensing using either satellite or aircraft multispectral (Moulin *et al.,* 1996) and hyperspectral imagers (Ustin *et al.,* 2004). In a similar way, ground-based remote sensing using portable digital cameras and reflectivity scanners for spectral analysis and optical measurements offers tremendous potential to complement and validate wide-area remote sensing classifications (Graham *et al.,* 2006; Chen and Welch, 2002; Treitz and Howarth, 1999; Holland *et al.,* 1997) and yield fine-scale information about microsites, physiology, and morphology that is impossible to measure from aircraft or satellites.

In the previous discussion, we introduced one of our earliest digital video sensor networks, which were used to monitor the behavior and activity patterns of nesting birds within artificial nest boxes. We have also installed a number of similar networked digital cameras throughout the James Reserve, ranging from fixed field-of-view cameras used to observe the physiologic status of plants and tower-based robotic pan/tilt/zoom (PTZ) cameras to track periodic plant growth changes (phenology) and wildlife activity to PTZ cameras mounted on the underside of two NIMS robots to map fine-scale and temporally dynamic attributes of vegetation, soil, insects, and environmental conditions beneath the instrument transects. These small, versatile RGB color digital cameras have been successfully calibrated to quantify changes in leaf surface area in woody and herbaceous perennials and to assess spectrally the photosynthetic activity and annual net uptake of carbon as a function of rainfall fluctuations in a desiccation-tolerant species of moss (Graham *et al.,* 2006; Mishler and Hamilton, 2002). Further studies to automate and extrapolate comparable measurements (spectrum and surface area) from hundreds to thousands of concurrently collected images via the tower cams and NIMS cams may provide a reliable and efficient methodology for scaling changes in small features to surface reflectance signatures that are detectable by satellite and airborne sensors.

Another class of video imager is being developed for the automated minirhizotron (AMR). Standard minirhizotrons (MRT) are field portable tools commonly used by soil ecologists to view microscopic features within the soil that surrounds a buried transparent cylinder. By repeated manual sampling, usually seasonally, measurable rates of root growth, mycorhizal fungi presence/absence, and soil structures can be determined. Our AMR is a unique version of an MRT that will soon be permanently installed inside a buried transparent acrylic tube, with wired connections to the surface. A small CCD camera fitted to a microscope lens is robotically controlled via a wireless network connection and can be remotely controlled to collect root images. A precision 2-axis camera positioning stepper-motor controller will allow repeat imagery to be captured at programmed time intervals. Currently a 200 × lens is being tested, but a 400 × lens may be possible with today's technology. Automated video content analysis techniques are being developed to acquire images and segment important biological features such as root hairs and fungal hyphae so that only imagery showing changes in predefined categories are actually archived by the DMS. Our first AMR prototype will be deployed in early 2006, and after testing, we expect to install an array of 15 AMR units by 2007.

In all of these cases, CENS is using relatively power-hungry, medium-resolution, off-the-shelf CCD imagers that require tethered connections to grid power sources or to nearby solar photovoltaic arrays for charging batteries. To overcome this limitation, CENS engineers in collaboration with an industrial partner have developed an extremely low power, radio-mote plus CMOS imager with on-board image-processing capabilities suitable for spectroscopic analysis, pattern/object detection, and movement detection (Rahimi *et al.,* 2005). Dubbed the CYCLOPS, this tiny unit will complement our untethered microclimate ENS systems, being installed in the nest boxes and other outdoor locations to monitor avian activity, measure plant phenology and growth, and estimate photosynthesis continuously. If successful, we anticipate using CYCLOPS imagers in our next generation of fixed field-of-view AMR and on smaller form factor NIMS platforms.

Multiscale infrastructure of fixed and mobile sensors to study soil processes and carbon balance

One of the fundamental questions of carbon balance in terrestrial environments relates to the role of below-ground biologic activity in ecosystem carbon flux. Above the plant canopy, eddy covariance methodologies and associated models exist for studying carbon flux in a single dimension; below the canopy, intra-system variations in carbon fluxes are difficult to measure, and as a result, there are few models characterizing the underlying regulatory dynamics. Soil respiration from vascular plant root systems, fungi, and microbial populations form a major flux of carbon at the soil/atmosphere interface.

In our research, working within a montane mixed-conifer forests, we ask the question whether soil surface measurements of energy balance and moisture profiles can be used to develop spatially explicit models of soil biological activity and CO_2 flux, which can then be validated by measurements at a limited number of discrete CO_2 sample sites. The means to simultaneously input signals from different instrument sources to then provide real-time estimates of carbon flux (mmol CO_2 respired $m^{-2}s^{-1}$) is an ambitious task. These values must then further be integrated with microscopic images of roots or soil microbes at scales that can detect events, not just averages (Fig. 1). Subsequent models predicting spatial and temporal scales of variation in soil CO_2 flux must be developed to be successful in meeting these goals.

AMARSS: Automated-minirhizotron and arrayed rhizosphere-soil sensors. High-resolution sensors mounted on mobile robotic platforms and coordinated with fixed soil and microclimate sensor arrays now provide the capacity to link soil and root measurements with mobile units measuring environmental conditions from the soil surface into the canopy (Kaiser *et al.,* 2004). We have developed models relating surface CO_2 flux to biological activity (Tang *et al.,* 2003, 2005; Tang and Baldocchi, 2005; Turcu *et al.,* 2005; Vargas *et al.,* 2005); and further to infer both biological activity and CO_2 flux across a forest floor from a surface energy balance. Our test bed transect (Fig. 1) consists of manual and robotic minirhizotrons with a resolution of up to 400 x, coupled to arrays of soil, plant, and atmospheric sensors. The soil sensors (CO_2, $NO_{-3,}$ H_2O, temperature, soil moisture content) are fixed, but measure the relevant parameters at multiple depths. The sensors are arrayed in a scale-free arrangement, extending 50 m long. Additionally, a cable-mounted mobile robotic node (NIMS) uses an IR thermal scanner system to map soil surface temperature, as well as above-ground profiles of wind, incident solar radiation, and relative humidity over each node in the fixed below-ground array. A 3-D laser scanner aides in building a precise model of tree and shrub canopies in order to model solar interception by leaves, branches, and the soil surfaces and to measure biomass volumetrically.

Past studies were able to measure large-scale outputs of CO_2 (e.g., eddy covariance methods), but could not predict the impacts of small-scale processes (N mineralization, chaotic water infiltration under unsaturated flows). Our new systems have begun to collect continuous measurement streams from the microclimate and soil arrays feeding data archives, which in turn provide inputs to drive temporal modeling of fluxes that integrate geospatial models across multiple time scales. *In situ* tools to view real-time data streams, analyses, and model outputs are now under development to aid in refining the sensor locations and sampling frequency. As external drivers such as precipitation and solar radiation are detected, or as soil sensors and minirhizotron observations detect pulses, above-ground mobile systems will be actuated providing enhanced resolution scans suitable for extrapolation and forecasting of discrete soil flux measurements to broader spatial scales.

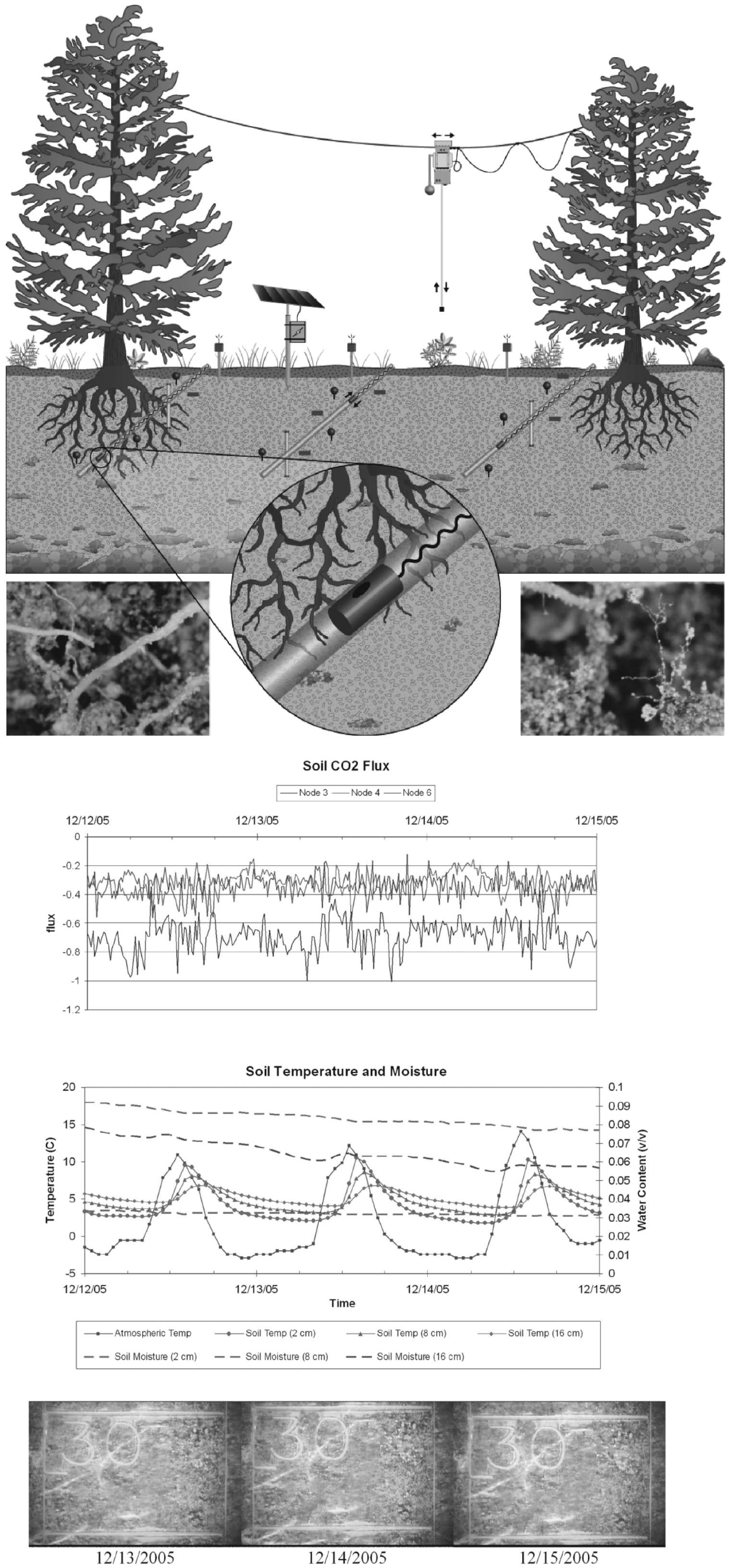

Figure 1. AMARSS (automated minirhizotron and arrayed rhizosphere sensor system) meets NIMS (networked infomechanical system) for a multi-scale study of below- and above-ground ecosystem processes. This below-ground soil sensor array measures continuous CO_2 flux, temperature, and moisture at three depths (2, 8, and 16 cm). Minirizotron images are collected daily and serve as training sets for automated minirhizotron system.

These studies will aid in dealing with the challenges of measuring carbon cycles with respect to the contribution of the lateral flow of air and respiration fluxes within the canopy. Eddy covariance measurements of CO_2 fluxes above the floor of a forest canopy are still not completely validated and thus require directed measurements of energy, carbon flux, primary productivity, and microclimate. In complex and sloping forested environments, variability in soil respiration, plant structural heterogeneity, and large lateral movements of air make closing the carbon loop even more difficult and thus offer many opportunities for basic research into the forest dynamics that can be applied to global carbon models.

CYBERINFRASTRUCTURE

Cyberinfrastructure is the coordinated aggregate of software, hardware, and other technologies, as well as human expertise, required to support current and future discoveries in science and engineering. The challenge of cyberinfrastructure is to integrate relevant and often disparate resources to provide a useful, usable, and enabling framework for research and discovery characterized by broad access and "end-to-end" coordination. Within a functional cyberinfrastructure (CI) for environmental and ecological observatories is the promise for rich feedback loops between environmental phenomena, observing systems, and experimenters in the field. These complex interactions require data formats, communication protocols, and software systems that provide scientists easy access to data, models, and computational resources. At CENS, we are exploring new CI that directly addresses these challenges, enabling the flow of data, models, and computation, and as a result, offering scientific investigators, whether they are in the laboratory or the field, new tools to help amplify and focus the power of observatories to achieve greater spatial and temporal resolution of phenomena. In our prototype systems we are working towards five CI capabilities: (1) data publication and archiving; (2) statistical analysis, visualization, and computing; (3) event specification, detection, and response; (4) analysis and computation; and (5) management and scheduling of observational resources.

Data management systems

Progress toward a full range of CI tools and services have focused on the development of our open source-based data management system (DMS), built around an SQL data engine with PHP and PERL scriptable interfaces. The current generation DMS schema archive sensor and image data provide support for metadata tags that are consistent with existing sensor and ecological meta languages (e.g., EML), incorporate a web-based graphical user interface (GUI) to browse data catalogs, and specify data types and time/date ranges, visually portraying data as graphs and exporting raw datasets (refer to <http://dms.jamesreserve.edu> for additional information). Several interfaces have been designed to allow scheduling of image acquisition, including programmed control over PTZ tower cams, scripts to summarize data, and error checking and sensor calibration transforms to detect and suppress data outliers.

Geographic information systems

The James Reserve maintains a geographic information system (GIS) based on the ArcGIS 9.2 software (ESRI, Inc., Redlands, CA). In late 2004, we contracted an aerial photography service to fly the James Reserve and the surrounding 300 ha watershed at ultra-fine resolution (10 cm/pixels). This 5 GB RGB scene was then georectified to a high-resolution LIDAR-derived digital elevation model (DEM) with $<$0.25 m pixel resolution in elevation. GPS-based coordinates were collected for all sensors and instruments, locations added to the GIS, and custom map symbols developed to simplify identification. According to ESRI, the makers of ArcGIS, we can expect full mySQL table read/write compatibility in the next update to their software. Work is underway to integrate DMS tables into the GIS so that geospatial model tools can be applied to data streams for rapid and interactive data display and interpolations. A similar approach is underway to integrate the open source (GNU) "R" statistical and graphical software language into the DMS (<www.r-project.org/>).

Finally, we have begun a prototype of a comprehensive data browser and viewer that is built around the GoogleEarth (GE) server (<http://earth.google.com/>). Similar to many 3-D scientific visualization systems, our GE prototype lets you fly across the James Reserve test bed, switch on layers that represent different ENS systems, and access archival and real-time data streams by clicking on the 3-D objects and selectively displaying data layers from our GIS (including precalculated geospatial models). Future versions of our GE system will include dynamic data display (time series) of archival data and the capability to select multiple data streams, specify particular geospatial models to apply to the data, and then view the product as a draped data layer.

CONCLUSIONS

Miniaturization now enables sensing, computation, and wireless communication to be combined in small, low-power devices. These devices can now be networked and embedded in the environment to reveal phenomena with unprecedented detail. Embedded networked sensing (ENS) systems are transforming how we observe physical processes, and these observations are leading to new scientific understanding of the environment. Fine-scale measurements have resulted in new models, new predictions, and a deeper appreciation for managing environmental resources in a growing number of applications. Through our design, development, and deployment activities we have found that effective embedded sensing is not always about the largest number of the smallest sensors. Robust, scalable, and flexible systems require a layered mix of observational resources, including sensor capabilities, networking, modeling, and user interaction. Because ecological observatories will create massive amounts of new data, there are important concerns as to how researchers will access these data streams in real time, how data will be analyzed and models developed, and how instrumentation used by individual researchers will be linked with data streams from the observatory instruments (Withey *et al.,* 2002). Our future observing systems will employ programmable, adaptive, and autonomous coordination among heterogeneous embedded devices to export information, not just raw data, and fuse this high-fidelity information with external data sources.

Continued refinement of applications of ENS technologies at CENS will be across larger and finer spatial scales, incorporating new and different sensors and sensing protocols, as well as enhanced tools specifically designed to assist the end user. While embedded sensing necessitated embedded computation and control, we are now seeing that facilities that enable embedded interpretation and modeling of data are also crucial (Estrin *et al.,* 2003). These capacities also provide for actuation, either through the activation of static nodes or by tasking mobile systems to respond to environmental events. Such facilities not only offer greater observational power, but also introduce concepts into our architecture that greatly aid manual interactive functionality.

Ecological investigation and forecasting require new tools for exploratory analysis, as well as formal modeling capabilities that draw from a hierarchy of inter- and multiscale observations linking environment, organisms, and responses. These functions are also no longer restricted to the laboratory, but are needed *within the ecosystem*. Future ecological observatories will incorporate these fundamental design concepts in order to reinvent the digital supply chain of strategic information from sensor to scientist.

ACKNOWLEDGMENTS

The work summarized in this paper is that of students, staff, and faculty of CENS. We greatly acknowledge the support of our sponsors, including the National Science Foundation, the Natural Reserve System, industrial partners, and the UC campus administrations. In particular, we want to acknowledge our intrepid field engineers, programmers, and hardware developers who worked very hard to make our original CMS run like the "Energizer Bunny"—to Michael Wimbrow, Michael Taggart, Kevin Browne, Sean Askay, Mohammad Rahimi, Thanos Boulis, Naim Busek, Vlad Bychkovskiy, Mohan Mysore, Eric Osterweil, and quite a few others, many thanks!

The research described herein is supported by several grants from the National Science Foundation, including our core CENS STC (award no. 0120778), NIMS ITR (award no. 0331481), AMARSS biocomplexity (award no. 0410408), and the authors' institutions.

REFERENCES

AIBS (American Institute for Biological Sciences) (2003). *Rationale, blueprint, and expectations for the National Ecological Observatory Network. Infrastructure for biology at regional to continental scales (IBRCS) working group*. White paper, March 2003.

ARZBERGER, P. (2004). *Sensors for environmental observatories*. Report of the NSF sponsored workshop, December 2004, WTEC, Baltimore, MD. http://www.wtec.org/seo/final (Last accessed December 2006).

BADECK, F., BONDEAU, A., BÖTTCHER, K., DOKTOR, D., LUCHT, W., SCHABER, J., and SITCH, S. (2004). Responses of spring phenology to climate change. *New Phytol.* **162,** 295.

BALDI, A. (1999). Microclimate and vegetation edge effects in a reedbed in Hungary. *Biodiv. Conserv.* **8,** 1697.

BROTHERS, T.S. (1993). Fragmentation and edge effects in central Indiana old-growth forests. *Nat. Areas J.* **13,** 268.

CADENASSO, M.L., TRAYNOR, M.M., and PICKETT, S.T.A. (1997). Functional location of forest edges: Gradients of multiple physical factors. *Can. J. For. Res.* **27,** 774.

CENS (2005). *Third year annual report*. http://research.cens.ucla.edu (Last accessed December 2006).

CHEN, J., FRANKLIN, J.F., and SPIES, T.A. (1992). Vegetation responses to edge environments in old-growth Douglas-fir forests. *Ecol. Appl.* **2,** 387.

CHEN, J., FRANKLIN, J.F., and SPIES, T.A. (1995). Growing-season microclimatic gradients from clear-cut edges into old-growth Douglas-fir forests. *Ecol. Appl.* **5,** 74.

CHEN, X., and WELCH, S.M. (2002). Use of nontopographical stereophotogrammetry to measure morphological characteristics of soybean plants. *Trans. Am. Soc. Agric. Eng.* **45,** 423.

ESTRIN, D., MICHENER, W., and BONITO, G. (2003). *Environmental cyberinfrastructure needs for distributed sensor* *networks*. Report of an NSF-sponsored workshop. UC San Diego, CA, Aug 12–14, 2003.

GRAHAM, E.A., HAMILTON, M.P., MISHLER, B.D., RUNDEL, P.W., and HANSEN, M.H. (2006). Use of a networked digital camera to estimate net CO_2 uptake of a desiccation tolerant moss. *Intern. J. Plant Sci*. **167,** 751.

HAMILTON, M. (2004). *CENS: New directions in wireless embedded networked sensing of natural and agricultural ecosystems. Converging technologies for agriculture and environment.* Sir Mark Oliphant Conference, Melbourne, Australia, Aug 9–12, 2004. http://www.jamesreserve.edu/staff/Oliphant_Report.pdf

HOLLAND, K.T., HOLMAN, R.A., LIPPMANN, T.C., and STANLEY, J. (1997). Practical use of video imagery in nearshore oceanographic field studies. *IEEE J. Ocean. Eng.* **22,** 81.

HOLMES, R.T., and SHERRY, T.W. (2001). Thirty year bird population trends in an unfragmented temperate deciduous forest: Importance of habitat change. *Auk* **118,** 589.

JACKSON, T.P., ROPER, T.J., CONRADT, L., JACKSON, M.J., and BENNETT, N.C. (2002). Alternative refuge strategies and their relation to thermophysiology in two sympatric rodents, *Parotomys brantsii* and *Otomys unisulcatus*. *J. Arid Environ*. **51,** 21.

KAISER, W., POTTIE, G., SRIVASTAVA, M., SUKHATME, G.S., VILLASENOR, J., and ESTRIN, D. (2004). *Networked Infomechanical Systems (NIMS) for Ambient Intelligence in Ambient Intelligence.* Berlin: Springer-Verlag.

MATLACK, G.R. (1993). Microenvironment variation within and among forest edge sites in the eastern United States. *Biol. Conserv*. **66,** 85.

MCCARTY, J.P. (2001). Ecological consequences of recent climate change. *J. Soc. Conserv. Biol*. **15,** 320.

MISHLER, B.D., and HAMILTON, M.P. (2002). The MossCam Project: The world's first remote-sensing project on moss ecology. *Am. Bryol. Lichen. Soc. Abstr. Contr. Pap.* **2002,** 32.

MOULIN, S., KERGOAT, L., VIOVY, N., and DEDIEU, G. (1996). Global-scale assessment of vegetation phenology using noaa/avhrr satellite measurements. *J. Clim.* **10,** 1154.

NRC (NATIONAL RESEARCH COUNCIL) (2001). *Grand Challenges in Environmental Sciences*. Washington, DC: The National Academies Press.

NRC (2003). *NEON: Addressing the Nation's Environmental Changes*. Washington DC: The National Academies Press.

NSF (NATIONAL SCIENCE FOUNDATION) (2000). *Environmental science and engineering for the 21st century*. www.nsf.gov/pubs/2000/nsb0022/reports/nsb0022. pdf (Last accessed December 2006).

NSF (2003). *Complexenvironmental systems: Synthesis for earth, life, and society in the 21st century*. NSF-ERE. http://www.nsf.gov/geo/ere/ereweb/ac-ere/acere_synthesis_rpt_full.pdf

PORTER, J., BERGER, A.R., P., BRAUN, H., BRYANT, P., GAGE, S., HANSEN, T., HANSON, P., LIN, C., LIN, F., KRATZ, T., MICHENER, W., SHAPIRO, S., and WILLIAMS, T. (2005). Wireless sensor networks for ecology. *BioScience* 55, 561.

RAHIMI, M., BAER, R., OBIMDINACHIO, I.I., GARCIA, J.C., WARRIOR, J., ESTRIN, D., and SRIVASTAVA, M. (2005). *Cyclops: In Situ image sensing and interpretation in wireless sensor networks.* ACM SenSys '05, Nov 2–4, 2005, San Diego, CA.

SENKOWSKY, S. (2005). Planning of NEON moves ahead. *BioScience* **55,** 106.

SYDEMAN, W.J., HESTER, M.M., THAYER, J.A., GRESS, F., MARTIN, P., and BUFFA, J. (2001). Climate change, reproductive performance and diet composition of marine birds in the southern California Current system, 1969–1997. *Prog. Ocean*. **49,** 309.

SZEWCZYK, R., OSTERWEIL, R.E., POLASTRE, J., HAMILTON, M., MAINWARING, A., and ESTRIN, D. (2004). Habitat monitoring with sensor networks. *Comm. ACM* **47,** 34.

TANG, J., BALDOCCHI, D.D., QI, Y., and XU, L. (2003). Assessing soil CO_2 efflux using continuous measurement of CO_2 profiles in soils with small solid-state sensors. *Agric. For. Meteor*. **118,** 207.

TANG, J., and BALDOCCHI, D.D. (2005). Spatial–temporal variation in soil respiration in an oak-grass savanna ecosystem in California and its partitioning into autotrophic and heterotrophic components. *Biogeochemistry* **73,** 183.

TANG, J., BALDOCCHI, D.D., and XU, L. (2005). Tree photosynthesis modulates soil respiration in a savanna ecosystem. *Glob. Change Biol*. **11,** 1298.

TREITZ, P., and HOWARTH, P. (1999). Hyperspectral remote sensing for estimating biophysical parameters of forest ecosystems. *Prog. Phys. Geogr*. **23,** 359.

TURCU, V.E., JONES, S.B., and ORR, D. (2005). Continuous soil carbon dioxide and oxygen measurements and estimation of gradient-based gaseous flux. *Vadose Zone J.* **4,** 1161.

USTIN, S.L., ROBERTS, D.A., GAMON, J.A., ASNER, G., and GREEN, R.O. (2004). Using imaging spectroscopy to study ecosystem processes and properties. *BioScience* **54,** 523.

VARGAS, R., ALLEN, M., SWENSON, W., and HAMILTON, M. (2005). *Soil embedded networked systems for studying soil carbon dynamics: The A-MARSS project.* Third USDA Symposium on Greenhouse Gases and Carbon Sequestration in Agriculture and Forestry. March 21–24, 2005, Baltimore, MD. http://soilcarboncenter.k-state.edu/conference/USDA Abstracts html/Abstract Vargas.htm

WITHEY, A., MICHENER, W., and TOOBY, P., Eds. (2002). *Scalable information networks for the environment (SINE).* Report of an NSF-sponsored workshop, San Diego Supercomputer Center, Oct 29–31, 2001.