Tansley review

Environmental sensor networks in ecological research

Author for correspondence:
Philip W. Rundel
Tel: +1 310 825 4072
Email: rundel@biology.ucla.edu

Received: *29 September 2008*
Accepted: *24 January 2009*

Philip W. Rundel[1,2], Eric A. Graham[1], Michael F. Allen[3], Jason C. Fisher[4] and Thomas C. Harmon[4]

[1]Center for Embedded Networked Sensing, University of California, Los Angeles, CA 90095, USA; [2]Department of Ecology and Evolutionary Biology, University of California, Los Angeles, CA 90095, USA; [3]Center for Conservation Biology and Department of Plant Pathology and Microbiology, University of California, Riverside, CA 92521, USA; [4]School of Engineering, University of California, Merced, CA 95344, USA

Contents

New Phytologist (2009) **182**: 589–607
doi: 10.1111/j.1469-8137.2009.02811.x

Key words: aquatic ecosystems, data management, imagers, mobile sensors, sensor networks, soil ecosystems, wireless sensors.

Summary

Environmental sensor networks offer a powerful combination of distributed sensing capacity, real-time data visualization and analysis, and integration with adjacent networks and remote sensing data streams. These advances have become a reality as a combined result of the continuing miniaturization of electronics, the availability of large data storage and computational capacity, and the pervasive connectivity of the Internet. Environmental sensor networks have been established and large new networks are planned for monitoring multiple habitats at many different scales. Projects range in spatial scale from continental systems designed to measure global change and environmental stability to those involved with the monitoring of only a few meters of forest edge in fragmented landscapes. Temporal measurements have ranged from the evaluation of sunfleck dynamics at scales of seconds, to daily CO_2 fluxes, to decadal shifts in temperatures. Above-ground sensor systems are partnered with subsurface soil measurement networks for physical and biological activity, together with aquatic and riparian sensor networks to measure groundwater fluxes and nutrient dynamics. More recently, complex sensors, such as networked digital cameras and microphones, as well as newly emerging sensors, are being integrated into sensor networks for hierarchical methods of sensing that promise a further understanding of our ecological systems by revealing previously unobservable phenomena.

I. Introduction

Ecological research is undergoing a major technological revolution as interfaces develop between environmental science, engineering and informational technology. These advances have been spurred by decreasing cost, size and weight, and improved reliability, of environmental sensing hardware and software. Coupled with the increased connectivity afforded by the Internet to transmit and share data, arrays of intelligent sensor networks are emerging as fundamental tools to address complex questions of myriad ecosystems.

Key to these advances has been the development of appropriate cyberinfrastructure, which comprises the computing systems, advanced instruments, data storage systems and data repositories, visualization environments and technically trained individuals linked together by software and high-performance communication networks to improve research productivity (Estrin *et al.*, 2003; Brunt *et al.*, 2007). Sensor networks coupled with associated cyberinfrastructure thus offer a powerful combination of distributed sensing capacity, internet and satellite communication, and computational tools that lend themselves to countless applications in ecological research. Moreover, new designs of sensor networks allow for the observation of systems in near-real time based on incoming data not only from local sources, but also from nested or adjacent networks, and from remote sensing data streams. These advances are providing a new and better understanding of our ecological systems by revealing previously unobservable phenomena and by allowing a potential for second generation of ecological questions that we have not yet addressed (Porter *et al.*, 2005).

Ecological sensor networks with highly developed cyberinfrastructure lie at the core of major new efforts to address fundamental issues of global change and environmental stability. The National Ecological Observatory Network (NEON), nearing implementation in the USA, is an integrated network of 20 regional observatories designed to gather long-term data on ecological responses of the biosphere to changes in land use and climate, and on feedbacks with the geosphere, hydrosphere and atmosphere (Keller *et al.*, 2008). Using standardized protocols and an open data policy, NEON will gather essential data for the development of the scientific understanding and theory required to manage the nation's ecological challenges. Similarly, the Global Lake Ecological Observatory Network (GLEON) is a network of limnologists, information technology experts and engineers with the goal of deploying a scalable, persistent network of lake ecology observatories to better understand key processes, such as the effects of climate and land-use change and episodic events on lake function. As with NEON, these observatories will consist of instrumented platforms on lakes around the world capable of sensing key limnological variables and moving the data in near-real time to web-accessible databases.

Many fundamental applications of sensor networks for ecological research involve the challenges of environmental monitoring across a wide range of spatial scales from centimeters to kilometers and temporal scales from fractions of a second to hours (Fig. 1). The ability to characterize the spatial and temporal scales of extreme events is of particular significance, as these have a disproportionate role in shaping the ecology, ecophysiology and evolution of plant species (Levine, 1992; Gaines & Denny, 1993; Gutschick & BassiriRad, 2003; Verstraeten *et al.*, 2008).

The conventional paradigm of increasing the density of fixed sensors in deployments to address issues of scale, however, is

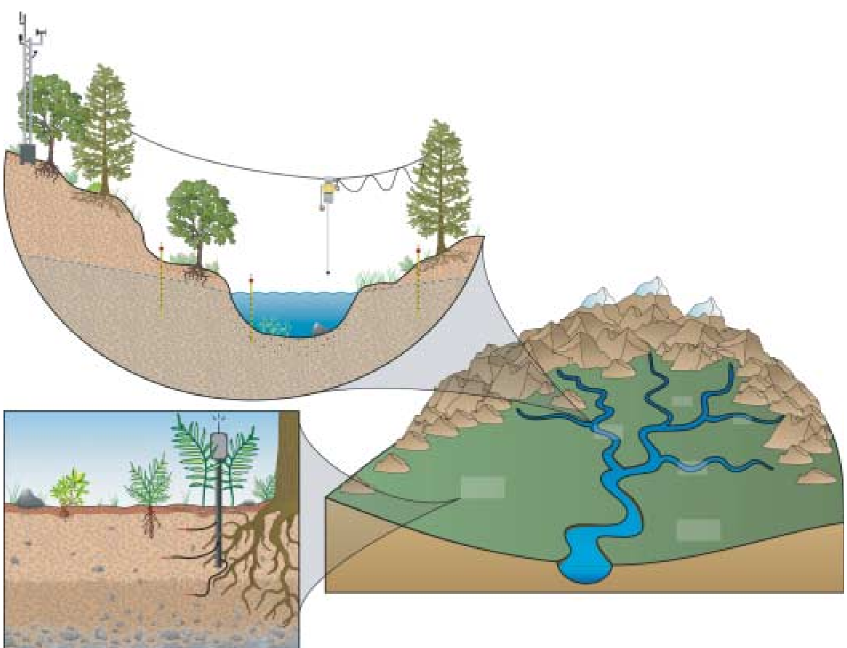

Fig. 1 Diagrammatic representation of a multiscale approach for environmental sensor networks across a landscape. Terrestrial, soil and/or aquatic sensor networks can all be used with multiple sensor modalities and both fixed and mobile sensing platforms. Drawing by Jason Fisher.

Table 1 Examples of major sensor modalities with comments on cost, reliability and power requirements

Sensor category	Example	Comments
Physical	Temperature (e.g. thermocouple, thermistor, IR sensor)	Inexpensive to intermediate cost, reliable, low power requirements
	Relative humidity	Intermediate, reliable, low power
	Leaf wetness	Inexpensive, reliable, low power
	Soil moisture	Inexpensive to moderate, issues with calibration and measurement units, low power; many choices
	PFD, total irradiance	Intermediate, reliable with calibration issues, low power
	Wind speed and direction	
	Cup anemometer	Inexpensive to intermediate, reliable, fails at low wind speed, low power
	Hot wire anemometer	Intermediate, less reliable, higher power
	2-D/3-D sonic anemometer	Intermediate to expensive, very reliable, moderate power
Chemical	Atmospheric carbon dioxide	Expensive, reliable, moderate power, requires careful calibration
	Soil carbon dioxide	Intermediate, reliable, low power, calibration?
	Soil carbon dioxide efflux	Expensive, reliable, moderate power, requires careful calibration
	Nitrate sensor	Expensive, under development for reliable terrestrial deployments
	Phosphorus sensor	Not available for terrestrial deployments
Biological	Digital imagers	Moderately expensive, reliable, moderate power; high bandwidth, software requirements
	Minirhizotron camera	Expensive, variable power requirements
	Sap flow sensors	Commercial probes moderate, control system needed; calibration issues
	Acoustic sensors	Moderate, reliable, moderate power, high bandwidth; software needs

2/3-D, two/three-dimensional; IR, infrared; PFD, photon flux density.

neither economically feasible nor desirable for a variety of reasons. For instance, the sampling and characterization of dynamic phenomena, such as sunflecks on the forest floor, with fixed sensors, whatever their number or position, will invariably be inefficient. Instead, a new paradigm in the design of sensor networks is multiscale sensing based on hierarchical systems that achieve efficient sampling of spatially and temporally dynamic phenomena by optimizing spatial coverage and sensor fidelity. The basic concept in multiscale sampling is that measurements from a low-resolution, wide-area sensor can be used to identify regions of interest, and then higher resolution sensors located in that region are awakened or focused onto that region and tasked for measurement.

As an example, using adaptive sampling, a wide field-of-view camera could sample an area at low resolution and communicate to a fixed sensor in that area to increase the sampling rate or to a mobile sensor to visit the area of interest and better characterize the spatial or temporal extent of the observation. Thus, sensor nodes do not necessarily need to be static, but can also be actively moved, such as on cables, tracks, robotic vehicles and aircraft (Baldocchi *et al.*, 1984; Clements *et al.*, 2003; Gamon *et al.*, 2006b; Laffea *et al.*, 2006). In our work, we have utilized cable-based robotic systems in long-term and rapidly deployable configurations, called Networked Info-Mechanical Systems (NIMS), to complement fixed sensor deployments (Fig. 1; Jordan *et al.*, 2007). The use of mobile sensing platforms allows for cyberinfrastructure with intelligent algorithms to utilize adaptive sampling protocols. Several statistical methods to adaptively sample data have been proposed in the literature, including stratified methods, in which initial sparse scans extract regions of high variability to be subsequently visited with more precision (Rahimi *et al.*, 2004); Gaussian process models, in which the 'informativeness' of a particular location is derived from the measurements made at already visited locations (Seeger, 2004); and kernel estimators, in which the value of the scalar field at any location is estimated using weighted linear regression, assuming that the closer two locations are, the higher the correlation between the values (Singh *et al.*, 2007).

There is great promise in sensor networks to expand on the traditional sensors for microclimate to involve new sensor modalities (Table 1). These include imagers and acoustic monitoring devices as biological sensors, which are discussed in the context of terrestrial sensor networks, and nutrient sensors, which are discussed in the context of soil and aquatic sensor networks. There are, nevertheless, a number of challenges in designing and deploying successful ecological sensor networks. Some of these issues relate to science-driven questions and requirements that are specific to terrestrial, soil or aquatic domains. Each of these domain needs is discussed in more detail below.

II. Terrestrial sensor networks

Traditional climate monitoring has been transformed by the connectivity afforded by the Internet, combining isolated climate stations into coarse-scale, terrestrial sensor networks that provide data relevant to environmental studies. An example can be seen in the United States National Weather Service, which first recruited cooperative observers in 1890, and now has more than 11 700 volunteers and 1900 airport-based installations, providing standardized, high-quality, near-real time meteorological data that are freely available through the National Weather Service Forecast Office (http://www.wrh.noaa.gov) and through long-lived commercial entities, such as The Weather Underground (http://www.wunderground.com). Regional climate monitoring and finer scale meteorological networks have been established to meet the needs of precision agriculture (Ley & Muzzy, 1992; Pierce & Elliott, 2008), and even fine-scale, experiment-driven sensor networks are growing in number. This section discusses both coarser and finer scale terrestrial sensor network deployments, with an emphasis on emerging technologies and newer strategies for data collection.

1. Sensor networks for ecosystem flux measurements

Micrometeorologists have been measuring CO_2 and water vapor exchange between vegetation and the atmosphere since the late 1950s and early 1960s. However, routine application of the eddy covariance methodologies and associated data management to allow continuous flux measurements did not occur until the 1980s, when technological advances were made in sonic anemometry, infrared spectrometry and digital computers. By the early 1990s, further technological developments, including larger data storage capacity and improved stability and precision in instruments, enabled scientists to build on pioneering ecosystem flux studies (Baldocchi *et al.*, 1987; Jarvis, 1989) to make defensible measurements of eddy fluxes for extended periods (Wofsy *et al.*, 1993; Vermetten *et al.*, 1994). The success of these new technologies, coupled with an increasing realization of the critical significance of ecosystem studies of carbon balance, led to the establishment of large multi-investigator experiments, such as the Boreal Ecosystem–Atmosphere Study (Sellers *et al.*, 1997) and the Northern Hemisphere Climate-Processes Land-Surface Experiment (Halldin *et al.*, 1999) that utilized sophisticated sensor networks.

The concept of a global network of long-term flux measurement sites had its genesis as early as 1993 in the science plan of the International Geosphere–Biosphere Program. This interest led to the establishment of the AmeriFlux network in 1997 to quantify spatial and temporal variation in exchanges of carbon, water and energy in major vegetation types across a range of disturbance histories and climatic conditions in the Americas, and to better understand processes regulating carbon assimilation, respiration and storage (Baldocchi *et al.*, 2001).

The AmeriFlux program soon joined with parallel programs in Europe, Japan and Latin America to form FLUXNET (www.fluxnet.ornl.gov), a self-described global network of micrometeorological tower sites that use eddy covariance methods to measure the exchanges of CO_2, water vapor and energy between terrestrial ecosystems and the atmosphere (Running *et al.*, 1999; Misson *et al.*, 2007). Over 500 tower sites with FLUXNET are now operating on a long-term and continuous basis with core data that include monthly and annual heat, water vapor and CO_2 flux, gap-filled flux products, ecological site data and remote-sensing products, with many sites deploying additional secondary networks of sensors. Data from European and US-American eddy covariance networks have allowed the analysis of seasonal patterns of assimilation and respiration in various ecosystems (Reichstein *et al.*, 2005), and the separation of net ecosystem exchange into gross ecosystem carbon uptake and ecosystem respiration (Falge *et al.*, 2002). The development of these instrumented towers over the past two decades has provided important practical lessons in the deployment and maintenance of complex multimodal sensor networks.

The issue of connecting these ground-based measures of ecosystem fluxes as provided by FLUXNET, and the broader issue of scaling these measurements up to global levels, has pointed to the critical interface between remote sensing and terrestrial sensor networks (Turner *et al.*, 2005). There have been a variety of efforts to bridge this gap, one of which has been through SpecNet (Spectral Network), a network of sites that combine optical sampling with eddy covariance data to address issues of scale (Gamon *et al.*, 2006a). SpecNet optical sampling focuses on spectral reflectance measurements and surface temperature measurements parallel to those generated from satellite sensors (Ustin *et al.*, 2004), but measured at finer spatial scales from towers, mobile trams and low-flying aircraft (Gamon *et al.*, 2006b; Hill *et al.*, 2006).

2. Targeted sensor networks

Both fixed and wireless sensor networks have been deployed successfully in a number of precision agriculture and ecological situations. Agricultural sensor networks provide data from fixed sensors in the field and from those embedded in mobile agricultural machines (Camilli *et al.*, 2007; Pierce & Elliott, 2008). Cyberinformatics and appropriate data modeling become key issues for precision agriculture, where farmers are less interested in masses of data than in decision-making based on acquired data (Beckwith *et al.*, 2004; Burrell *et al.*, 2004).

Ecologists have used wired networks of temperature and light sensors for decades. More recently, however, a number of research groups have successfully developed wireless sensor networks to meet specific research needs for remote sites (Polastre *et al.*, 2004; Porter *et al.*, 2005; Tolle *et al.*, 2005; Collins *et al.*, 2006).

Our Extensible Sensing System (ESS) at the James Reserve in the San Jacinto Mountains of southern California continuously monitors ambient microclimate below and above ground in more than 100 locations with a mix of wired and wireless networks within a 25-ha study area (Hamilton *et al.*, 2007). Individual nodes, each with up to eight sensors, are deployed

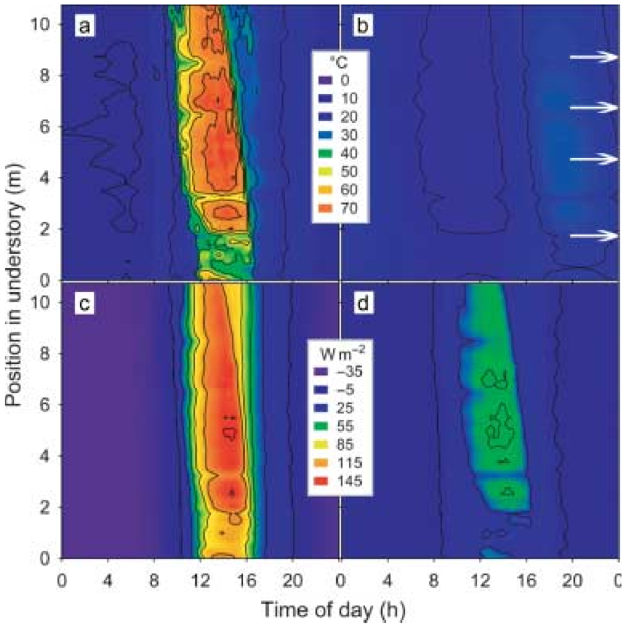

Fig. 2 An example of the density of data collected by a combined fixed and mobile wireless sensor array; data were collected for 24 h along a 10.75-m transect: (a) measured soil surface temperatures every 0.25 m via a mobile sensor platform; (b) measured (indicated by arrows) and calculated soil temperatures at 8 cm depth using soil temperature models; (c) calculated soil heat flux at the surface; and (d) calculated heat storage between the surface and 8 cm depth. Data from E. A. Graham *et al*. (unpublished).

along transects and in dense patches, crossing all major ecosystems and environments on the Reserve. Sensor modalities in the ESS include microclimate sensors, such as for temperature, humidity and photosynthetically active radiation (PAR), as well as a variety of imagers and acoustic sensors. Fixed sensors from the James Reserve networks have been successfully used in conjunction with mobile NIMS units and ecosystem energy flux models to provide a broad temporal and spatial analysis of patterns of soil surface energy balance (Fig. 2).

A notable example of wireless cyberinfrastructure providing core support to ecological research can be seen in the cyber-network of research sites in southern California (Cayan *et al.*, 2003). This network comprises 11 telecommunication sites, seven of which are solar powered, which connect 24 weather stations, three hydrological stations and 13 remote cameras to the Internet via the collaborative infrastructure of the High Performance Wireless Research and Education Network (HPWREN; hpwren.ucsd.edu). The connectivity allows researchers to employ high-bandwidth instruments, such as imaging systems used to measure and monitor ecological and environmental systems, as well as to extend the number and range of conventional remote sensing devices in the terrestrial domain (Hansen *et al.*, 2002).

As mentioned above, there has been increasing interest in the addition of new sensor modalities to sensor networks, such as, for example, with imaging, ecophysiological measurements such as sap flow, acoustic monitoring and biosensors. Image processing has been used in agricultural studies that combine automatic image capture, analysis and plant physiology (e.g. Slaughter *et al.*, 2008). Ecophysiological studies using cameras range from the detection of CO_2 fluxes in a desiccation-tolerant moss (Graham *et al.*, 2006) to quantitative phenological studies in woody species (Richardson *et al.*, 2007; Graham *et al.*, 2008). The proliferation of Internet-connected cameras that are situated in many natural ecological areas or human-dominated systems provides both challenges and opportunities for image analysis and data reduction. Although many of these systems involve fixed cameras, the addition of pan-tilt-zoom cameras to Internet-connected sensor networks provides a direct means of actuated control over these sensors (Graham *et al.*, 2008). Biosensors are in their early stages of development, but show great promise. Sapflow sensors can be readily added to wireless networks (Burgess & Dawson, 2008), and sensors to measure nutrient concentrations are being developed for soil and aquatic ecosystems, as described below.

We have had notable success in targeted short-term deployments of mobile NIMS to address a variety of ecological research questions. Indeed, although autonomous networks of sensors may seem attractive, early practical experience has indicated the difficulty of specifying field requirements in advance to operate systems remotely. Thus, many of our deployments are now based on dynamic ‘human in the loop’ scenarios (Wallis *et al.*, 2007), where teams regularly conduct short-term campaigns to collect data. One of these deployments established a replicated set of understory transect measurements of microclimate across the sharp boundary from open clearing to primary tropical rainforest at the La Selva Biological Station in Costa Rica. These measurements have allowed us to examine the diurnal dynamics of microclimate change in a manner that was not possible previously (Fig. 3).

3. Plant–animal interactions

Mobile, networked sensors for environmental monitoring can also be carried by people or animals (Burrell *et al.*, 2004). Although this area of research has a strong zoological and behavioral ecological orientation, systems collecting data on patterns of microclimate and animal–plant interactions, such as herbivory, pollination and seed dispersal, are highly relevant to plant biologists (Cooke *et al.*, 2004; Wikelski *et al.*, 2007). These tracking systems range from highly localized ones, using very high-frequency (VHF) radio-telemetry systems, to satellite-linked systems.

One of the most innovative examples of wireless data collection for large animal tracking is ZebraNet, a system that uses a peer-to-peer network to deliver logged data back to researchers (Juang *et al.*, 2002). The predominant satellite-based system for tracking wildlife is called Argos, a joint venture between the Centre National d’Etudes Spatiales (CNES), the National Aeronautics and Space Administration

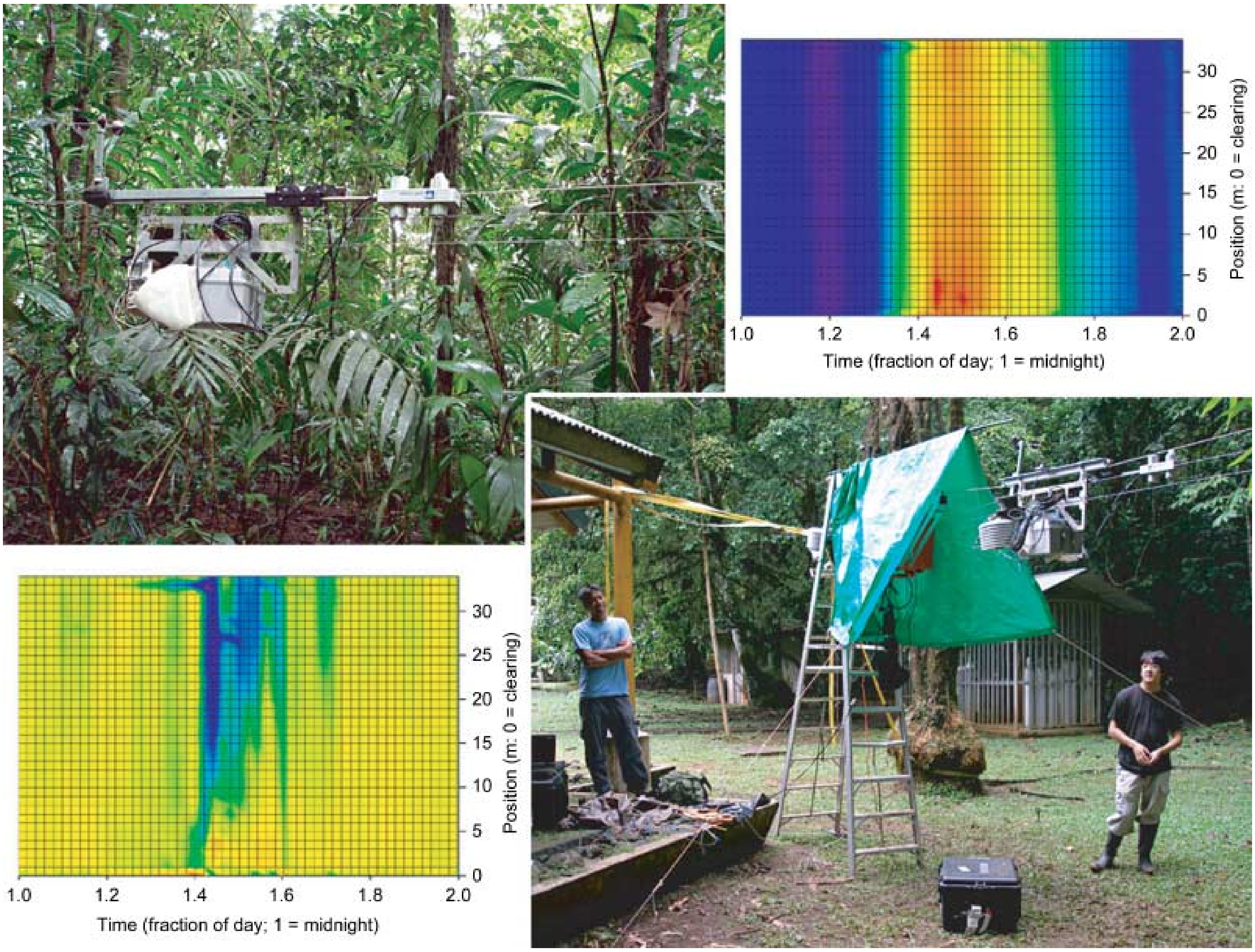

Fig. 3 Use of a mobile sensor platform to measure spatial and temporal patterns of understory microclimate at La Selva Biological Station, Costa Rica. The horizontal node (top left panel) autonomously traveled over an understory transect of 30 m carrying micrometeorological sensors. Stationary sensors and control of the horizontal node were located in a clearing at one end of the transect (bottom right panel). The panels show 24 h of 5-min air temperature data collected at different positions along the transect as absolute temperature (top right: temperature range, 22–30°C) and values relative to the clearing temperature (bottom left: temperature range, –1.0 to 1.0°C).

(NASA) and the National Oceanic and Atmospheric Administration (NOAA).

One of the newest networked systems developed for animal tracking over coarse spatial scales in tropical forests is the Automated Radio-Telemetry System (ARTS) on Barro Colorado Island in Panama. Based on the concept of radio-telemetry systems used to track satellites, ARTS employs a multiple antenna system and software to triangulate transmitter signals and send the resulting information about the location of an animal to a mapping program on a computer. This system has now been used with reasonable success to track ecologically important vertebrates (Cofoot *et al.*, 2008).

III. Soil sensor networks

Global concerns about the management of carbon and nutrient fluxes rest on an improved understanding of the exchanges that occur between a myriad of organisms, and coupling these interactions to the exchange between soil and atmosphere. CO_2 is primarily fixed in terrestrial ecosystems by plants, and the major recipients of the fixed carbon are plant roots and mycorrhizal fungi. They, in turn, access nutrients mostly following the decomposition of the plant parts. To date, these exchanges have been largely black-boxed, with exchange rates provided by coarse-scale inputs and outputs. A new approach is to place a network of sensors and imagers into the field to measure naturally occurring dynamics and interactions to evaluate the responses of multiple variables simultaneously (Fig. 1).

Sensor technology has the potential to tell us how the ecosystem partitions dynamics in real time. An example is the demonstration of the temporal dynamics in autotrophic versus heterotrophic respiration in semi-arid central California by Baldocchi and colleagues (e.g. Tang *et al.*, 2005). Pieces of the

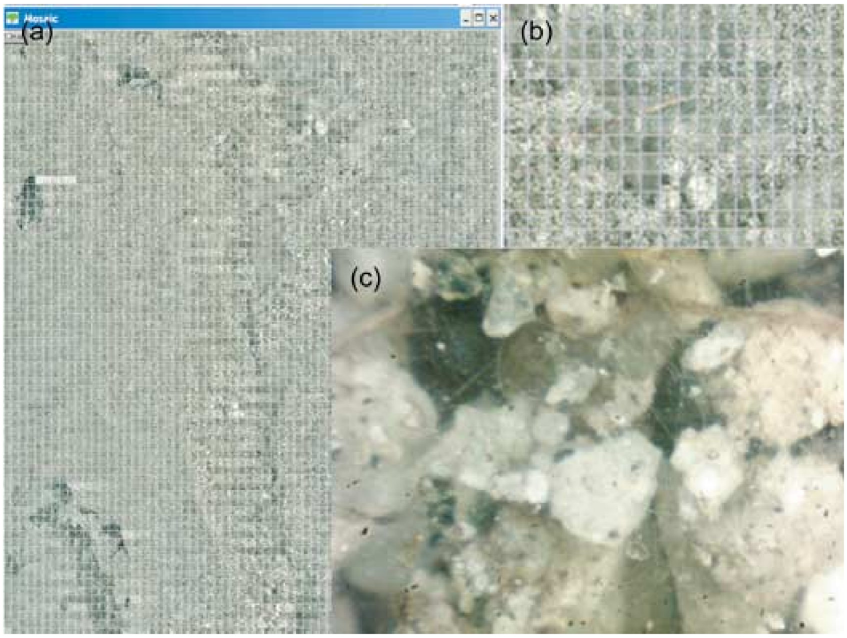

Fig. 4 Automated minirhizotron (AMR) test image from the James Reserve, California, USA. The camera takes a 1-mm^2 high-resolution image completing the scan of each tube. These images can be taken using a defined pattern within the tube, scanning the complete tube surface, or returning to individual points of interest. The individual images are then stitched together to form a mosaic of the tube surface. (a) Mosaic view of *c.* 30% of a single tube showing an overview of root and soil channels. By focusing on different areas of the mosaic, individual roots can be observed (b) and, by focusing on individual high-resolution images, roots, soil particles, and individual hyphae (c) can be seen and monitored. Using this test mode, we observed that some individual hyphae live for weeks or longer (e.g. coarse runner hyphae of arbuscular mycorrhizal fungi), whereas some of the finer hyphae are produced and disappear with days.

respiration puzzle have been pulled together over the past decade. Högberg *et al.* (2001) girdled *c.* 360 trees and measured soil respiration over a 2-month study, and reported that much of the soil respiration came from new photosynthate. Although a unique and important study, this method has a number of acknowledged problems, not least of which is the loss of those trees for additional research. Tang *et al.* (2005) undertook continuous measurement of soil respiration (using solid-state Vaisala sensors), coupled with eddy covariance measurements of total stand CO_2 fluxes. Normally, daytime respiration is calculated by subtracting the night-time respiration from the daytime total flux, and correcting for temperature. However, on coupling the soil sensors, they found a pulse of CO_2 coming from the soil that was decoupled from temperature, indicating a 7–12-h lag from photosynthesis until the carbon was received by the roots and mycorrhizal fungi. Without coupling soil sensors, it would have been predicted that there was more daytime soil respiration than actually occurred. This has the potential to have rather dramatic impacts on carbon sequestration models.

1. Soil sensor/imager approach

Taking apart black boxes requires more than simply looking at physical or chemical measurements of ecosystem dynamics. It also requires being able to observe the organisms responsible for those dynamics. *In situ* soil sensing systems for the measurement of CO_2 fluxes with root growth are now available, providing interesting insights into ecosystem functioning (e.g. Tang & Baldocchi, 2005; Tang *et al.*, 2005; Baldocchi *et al.*, 2006). Expanding the range of interactive sensors and replicating deployments in time and space are where sensor networks can be of greatest utility.

Roots have been studied using direct coring, root in-growth bags and minirhizotrons. The problem with focusing only on roots is that they have both metabolic and growth respiration, and their lifespans are too long for production and death to account for short-term or often even seasonal dynamics. Fungi comprise the second largest biomass group in most soils, but their dynamics are rarely studied in the field. Interestingly, individual hyphae grow and die at time scales of days to weeks (e.g. Hobbie & Wallander, 2006; Johnson *et al.*, 2006) that tie very closely to seasonal ecosystem dynamics and even shorter time scale events (Allen, 1993).

Newer automated minirhizotron (AMR) units have the potential to track both root and fungal dynamics *in situ* (Allen *et al.*, 2007), imaging soil volumes multiple times per day. Although these units are still in the testing phase, their use within a soil sensor network is promising (Fig. 4). Part of the problem with studying fine roots and fungal hyphae is simply the timing of production and disappearance. Stewart & Frank (2008) found that monthly measurements used to track root turnover were inadequate, and 3-d intervals were required. Fine roots may grow and die quickly, or can live for years, and rhizomorphs and coarse hyphae often have long life spans (Allen *et al.*, 2003). However, in response to events, rapid changes can occur even between daily observations.

Because the soil must be disturbed to establish a soil sensor network, the use of as much preliminary data as possible for situating sensors is key. Stover *et al.* (2007) used ground-penetrating radar (GPR) to track coarse root turnover. This instrument can provide initial information on the depth to rocks or water table, and the distribution of important features, such as coarse roots or artifacts. At the James Reserve, we were able to determine whether the locations of our sensor nodes were anomalous or representative of a range of characteristics,

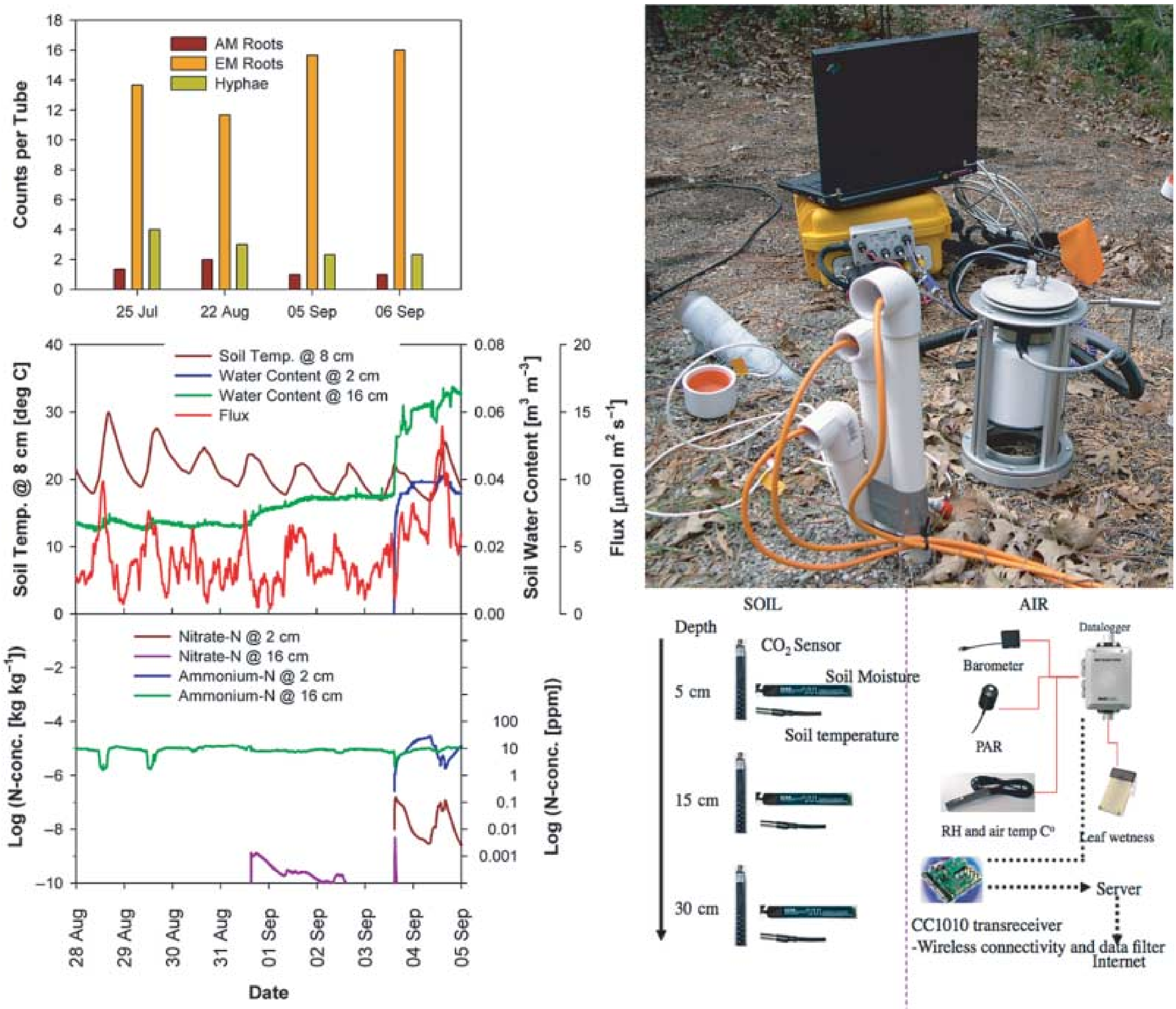

Fig. 5 Sensor output and counts of arbuscular mycorrhizal (AM) and ectomycorrhizal (EM) roots, and rhizomorph hyphae, during a monsoonal event in September 2007 at the James Reserve, California, USA. Shown (left) are the counts per minirhizotron tube, soil temperature, water content, soil CO_2 flux (calculated according to Vargas & Allen, 2008a) and soil nitrate and ammonium concentration. The sensors used include nitrate, ammonium, CO_2, soil water, temperature, photosynthetically active radiation (PAR) and barometric pressure, all needed to provide direct measurements of concentration and to calculate fluxes (see text). The upper right photograph is a location with a minirhizotron tube, entry points for sensors and a LiCor 8100 soil CO_2 flux system used to test against flux models (Vargas & Allen, 2008a).

including depth, rocks, coarse roots or other features. In addition, at the James Reserve, $\delta^{14}C$ measurements indicated that the coarse roots were too long lived for measurements within the time frames of interest to us (a mean of 17 yr for roots > 1 mm; Vargas & Allen, 2008a).

Because cores must be removed to insert tubes (for minirhizotrons and sensors), these cores should also be used for valuable baseline characterization of soil nutrients and texture. The texture is of special concern, as the calculation of tortuosity (ξ) is essential for modeling the amount of air space, which is tied to calculations of CO_2 production or respiration.

We have integrated a three-dimensional array of sensors, including sensors for CO_2 concentration, T, θ, NO_3^--N and NH_4^+-N, using a sensor network. These data are then used to calculate fluxes based on Fick's first law of diffusion. To calculate the fluxes (Fig. 5), it is also necessary to couple these data with the soil texture (which is used to determine tortuosity), soil moisture (coupled with texture to determine air-filled porosity), temperature (with pressure to determine the diffusivity in the soil) and atmospheric boundary conditions (to determine the ratio of diffusivity in the soil to that in the atmosphere, the driving gradient) necessary to model fluxes (Vargas & Allen, 2008a). There are four levels of calibration used to ensure the integrity of the data. The sensors require periodic calibration. For example, we recalibrate CO_2 sensors every 6 months. The modeled respiration rates are routinely tested against chamber CO_2 measurement systems (e.g. LiCor 8100) or eddy flux towers to evaluate performance. Having multiple sensors at a location allows for the detection of anomalies limited to a single sensor. The outputs of the models are then coupled to both conventional minirhizotron (CMR) or newer AMR imaging systems. This allows us to visualize if 'anomalies' are sensor outliers, or if there is a concentration (or dearth) of biological activity due to fine-scale patch structure common in soils (e.g. Klironomos *et al.*, 1999).

2. Sensing soil heterogeneity

One of the difficulties in soil ecology is defining where and how densely to place sensor nodes. Soil is exceedingly heterogeneous and thus must be sampled at spatial and temporal densities exceeding those for above-ground systems. Sensor networks are thus ideal for use in a physically dense array, such that the spatial structure can be discerned and often placed into a dynamic framework as patches become occupied, depleted and opened again. In addition, using a dense time array, lags and hysteresis can be identified. Finally, both acute and chronic perturbations can be studied over longer time scales with a stable network.

At the James Reserve, networked sensors provide readings at 5-min intervals, and minirhizotron readings are taken weekly, with intermittent daily campaigns. An example output from a single node is shown in Fig. 5. It is critical to note that not all sensor data are appropriate at all times (e.g. the nitrate and ammonium data in the extremely dry soils need to be dropped because of a lack of soil contact). Just as importantly, we have found that coarse hyphae can only occasionally be seen using CMR (Fig. 4) and need to be re-evaluated in the light of the AMR image outputs. Nevertheless, we have been able to begin to put together pictures of dynamics that are not observable using conventional approaches.

Many ecosystems are physically highly patchy. At the James Reserve, a semi-arid mixed conifer forest, there are light gaps and small-to-large meadows scattered across a complex terrain. Using a multiscale sensor network approach, images taken from a tower overlooking the underground study nodes found that shadows covered some nodes earlier than others. These shadows resulted in lower soil temperatures, and subsequently directly changed the diffusion and the measured soil respiration. Snow and rainfall also differentially occur across locations, creating dramatic differences in respiration, moisture extraction and nitrogen mineralization and uptake at quite fine scales. These result in very large differences between sites. We are just beginning to analyze these fine-scale spatial differences, but our preliminary estimates suggest that, when using random or daily measurements of respiration, the cumulative CO_2 released can be incorrect by 80% or more within 20 d.

Because above-soil canopies are not uniform, we also studied a soil transect within our sensor network running from a forest into a meadow (Vargas & Allen, 2008b). In that case, the hysteresis associated with photosynthate pumping in the forest disappeared in the meadow. Respiration was directly associated with diel temperature fluctuations.

3. Sampling remote disturbance events

One benefit of sensors and AMR units is that data can be obtained through significant disturbance events that occur when an investigator is not present. These can include extreme conditions of short-duration or severe events that alter long-term productivity. One such event studied was Hurricane Wilma that entered the Yucatan Peninsula in October 2005. The storm itself was far too severe (200 km h^{-1} winds, 1500 mm rainfall) for investigators to be at the site, and it took almost 2 months before investigators could reach the site after the storm. However, the sensors had worked well into the storm, before the flooding shorted out the battery system (Allen *et al.*, 2007). Some of the discoveries enabled by the use of this autonomous sensor network included the observation that the drop in barometric pressure probably did not result in a major degassing of the soil CO_2, apparently because the water had already saturated the soil, replacing soil air pockets. Thus, the water probably forced out the CO_2 and, as a result of low O_2 tension, respiration initially was low. Thereafter, surface litter rapidly decomposed because of the high moisture and high temperatures. The higher temperature was caused by intense radiation due to the loss in leaf area resulting from the winds and rapid drop in barometric pressure. The hysteresis pattern observed before the hurricane changed dramatically afterwards, apparently in response to a decoupling of respiration from night-time temperatures (Vargas & Allen, 2008c). This tells us that multiple and often unknown mechanisms account for major changes in ecosystem functioning as a result of perturbation. Having more systems in the field to track more and different types of events could provide a dramatic improvement in our understanding of major disturbances.

IV. Aquatic sensor networks

Aquatic sensors have been employed for decades on moorings and gauging stations to record time series for basic water parameters, such as temperature, stage-based flow and specific conductance (for salinity), and for above-water meteorological sensors. As more aquatic sensors are becoming accessible, conceptual models will be more readily tested and refined (Gawne *et al.*, 2007). Figure 6 illustrates a hypothetical sensor network focused on the observation of distributed environmental properties as they relate to macrophyte community structure (Tremp, 2007). Integrated data streams from such networks can be used to characterize higher order environmental

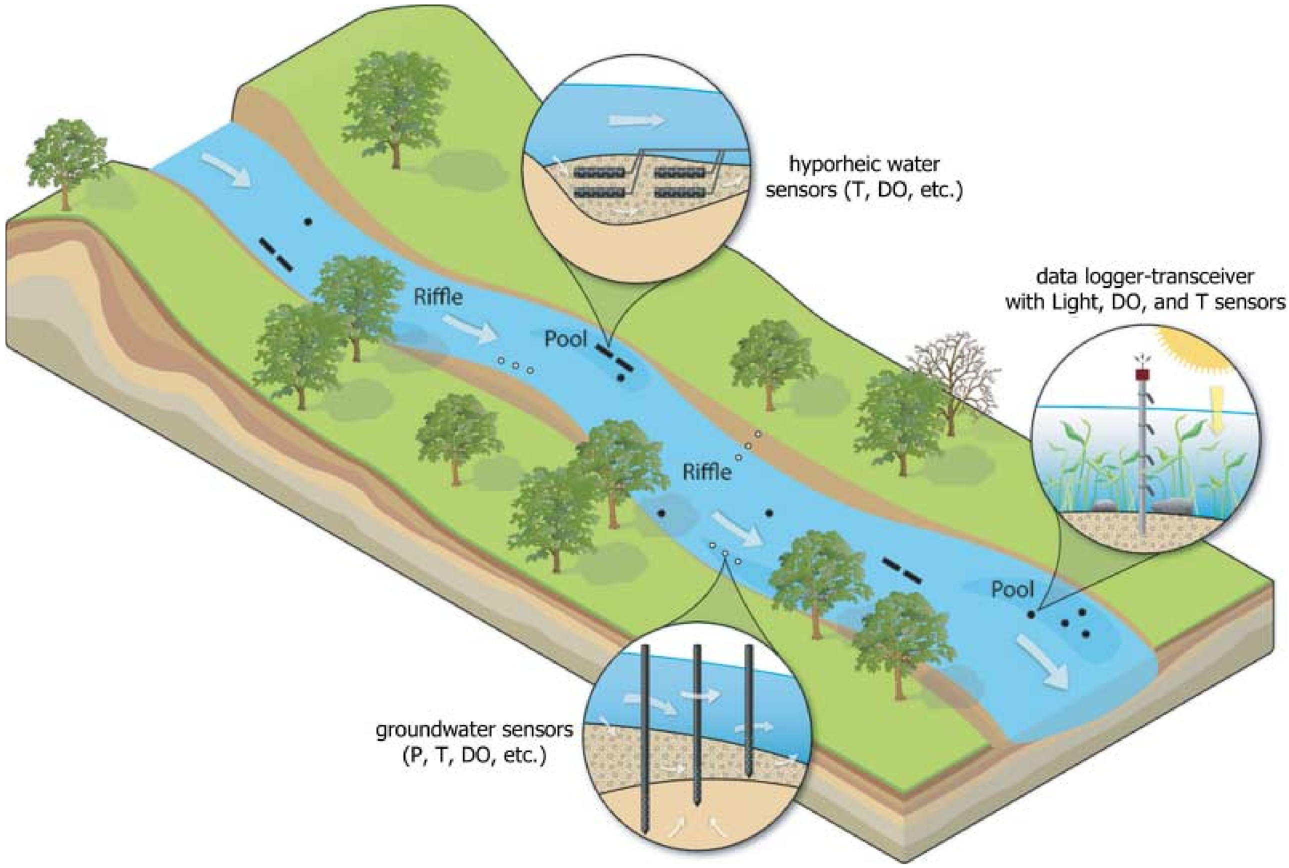

Fig. 6 Hypothetical deployment of an aquatic sensor network sampling pool and riffle patterns along a stream course, with positions of hyporheic water samplers and piezometers. DO, dissolved oxygen. Drawing by Jason Fisher.

properties of aquatic and riparian ecosystems. For example, moorings instrumented with temperature, light, dissolved oxygen (DO) and meteorological sensors have been used to characterize the primary productivity and respiration rates in rivers (e.g. Bott *et al.*, 2006) and lakes (e.g. Coloso *et al.*, 2008). In addition to observing local phenomena, these sensor networks can support scientific inquiry at the continental (Montgomery *et al.*, 2007) and global scale in the context of oceans (Dong *et al.*, 2008; Forget *et al.*, 2008). This section discusses existing and developing sensor network deployment strategies for aquatic and riparian ecosystems. It begins with a brief overview of currently available sensors and emerging sensors for aquatic observations, and extends to a discussion of sensor networks for making higher order observations of streams or rivers, lakes and groundwater.

1. Aquatic sensor modalities

The modes of physical, chemical and biological sensing useful in aquatic networks have been detailed elsewhere (Daly *et al.*, 2004; Goldman *et al.*, 2007; Johnson KS *et al.*, 2007; Prien, 2007). Physical sensors are the most reliable in the aquatic realm and include the previously discussed meteorological sensors, as well as evaporation, oxygen transfer and other processes at the air–water interface. Physical sensors for water pressure (depth), light penetration and flow velocity are also commonly deployed in aquatic systems. Reliable chemical sensors are available for several water properties, including salinity (in terms of specific conductance) and DO, which have been developing rapidly over the past decade, and long-term deployments are now common for both electrochemical (e.g. Clark cells) and optical luminescent DO sensors (optodes) (Tengberg *et al.*, 2006). The Alliance for Coastal Technologies (ACT) has completed performance demonstrations on several commercial DO sensors, mainly in marine settings (ACT, 2004), and results suggest that 2-wk to 1-month service intervals may be necessary, depending on local biofouling conditions. Other commonly deployed chemical sensors include those for oxidation–reduction potential (ORP), total suspended solids (TSS), nutrients (N, P), dissolved organic matter (e.g. CDOM) and indicators of primary production (e.g. chlorophyll). Among these, electrochemical sensors, such as pH, ORP and various ion selective electrodes (ISEs), remain unsuitable for long-term autonomous deployments within networks as their responses tend to drift excessively over time in the absence of frequent servicing. However, it is encouraging that several long-term deployment successes have been reported for nitrate ISEs in natural streams and canals (Le Goff *et al.*, 2003; Scholefield *et al.*, 2005). When more accurate assessments are necessary, robust ultraviolet–visible (UV/Vis) absorption (Johnson & Coletti, 2002) and flow cell analyzers (ACT, 2008) are now commercially available for nitrate, and are becoming available for dissolved and filterable phosphorus (ACT, 2008). Both electrochemical (Bobacka *et al.*, 2008) and optical (McDonagh *et al.*, 2008) sensing modes relevant to nitrogen and phosphorus species remain active research areas.

The observation of TSS is important in aquatic systems, particularly in the context of light penetration in the water column. Commercial models can be deployed reliably for as long as 2 wk in systems subject to biofouling (ACT, 2007), and probably significantly longer in nutrient-limited freshwater systems.

Sensors for aquatic flora and fauna are available to a much lesser extent relative to those for physical and chemical properties. Remote sensing platforms, such as hyperspectral imagers, have been used effectively to map vegetation in aquatic ecosystems (e.g. Hestir *et al.*, 2008). Distributed, embedded sensing technologies, including local imaging platforms discussed above, can provide high-resolution spatio-temporal data to complement remote sensing products, which are typically coarser in time and space and broader in spatial coverage. In terms of chemical sensing, fluorometers for indicating CDOM, *in vivo* chlorophyll-*a*, cyanobacteria and other parameters are now commercially available, and several models have been performance tested (ACT, 2006) and have shown excellent promise for observations coordinated with DO, primary production, eutrophication and other issues.

Flow-through cameras equipped with image classification software are available for the *in situ* identification and enumeration of phytoplankton in the water column (Bowen *et al.*, 2006). Similar coarser scale systems are used to identify and enumerate fish in engineered settings, such as fish ladders (Olson & Sosik, 2007; Sosik & Olson, 2007). As noted for terrestrial systems, there are potentially many more applications in the context of aquatic ecosystems for imagers as sensors in multiscale networks.

2. Sensor networks in rivers and lakes

As with terrestrial systems, both static and mobile deployment modes are used in aquatic systems. In general, many of the same types of sensor are carried in both modes, and the key difference is whether the observational objectives are related to time series or synoptic data or both. For observations in rivers and streams, the gauging station mode for static deployments is the most common. Driven mainly by governmental regulatory needs, coarse-scale networks of such stations exist to measure flow and basic water quality, typically temperature and salinity, throughout river basins, such as the California Digital Exchange Center (CDEC) for the Sacramento–San Joaquin river basins. More complex stations, such as the Columbia River (CORIE) Observation Network, are being developed which are equipped with multiparameter water quality sondes and acoustic Doppler current profilers (ADCPs) for mapping the passing velocity field under different flow regimes (Dang *et al.*, 2007). Such systems are becoming increasingly necessary in human-dominated watersheds, where environmental flows must be managed in terms of quantity and quality to sustain aquatic habitat in the face of other demands on water.

For lentic systems, moorings or tethered buoys have been used to assess basic water quality and key derived metrics, such as primary production (e.g. Gawne *et al.*, 2007; Coloso *et al.*, 2008). Typical buoyed platforms include basic meteorological sensors (including solar radiation) as well as multilevel water temperature thermistor chains, DO, submerged PAR sensors and other water quality parameter sensors. Using primary production/respiration (PP/R) models, the limnologists are able to integrate the network's data stream into PP/R time series. Coloso *et al.* (2008) examined the variation of gross primary production (GPP) and respiration horizontally and vertically in a lake using high-frequency DO observations to reveal that, although GPP declined sharply with depth, respiration was unrelated to depth. In a river restoration project, a similar network was used to assess changes in the introduction of air into the lower water layers, GPP, respiration and net daily metabolism (NDM) before and after canal backfilling, and after the restoration of continuous flow through the river channel (Colangelo, 2007).

Less well tested are sensor systems that support investigation into aquatic plant ecology questions at the terrestrial–aquatic margins, such as in wetlands and in littoral zones associated with lentic and lotic systems (Gratton *et al.*, 2008; Istvánovics *et al.*, 2008). These types of questions could be more efficiently addressed with support from terrestrial and aquatic sensor systems deployed to assess local environmental conditions above the water surface (e.g. vegetation type and cover, air temperature, humidity, PAR, wind), within the water column (e.g. stage, velocity, light transmission, water quality) and within the benthic zone (e.g. groundwater seepage rates, water quality).

Static sensor networks deployed on gauging stations or moored platforms are effective for providing time series data, and are acceptable when stream cross-sections and lakes are reasonably well mixed. There are many applications, however, where understanding stream community structure dictates the need for greater spatio-temporal observational coverage (Johnson RK *et al.*, 2007; Tremp, 2007). In lakes prone to stratification, vertical profiling capabilities may be necessary; moorings with this capability are commercially available and have been used successfully by oceanographers and limnologists (e.g. Doherty *et al.*, 1999; Reynolds-Fleming *et al.*, 2002). More recently, the tethered robotic NIMS discussed in the terrestrial network section was modified for application in lakes and rivers. In one application, NIMS was used to

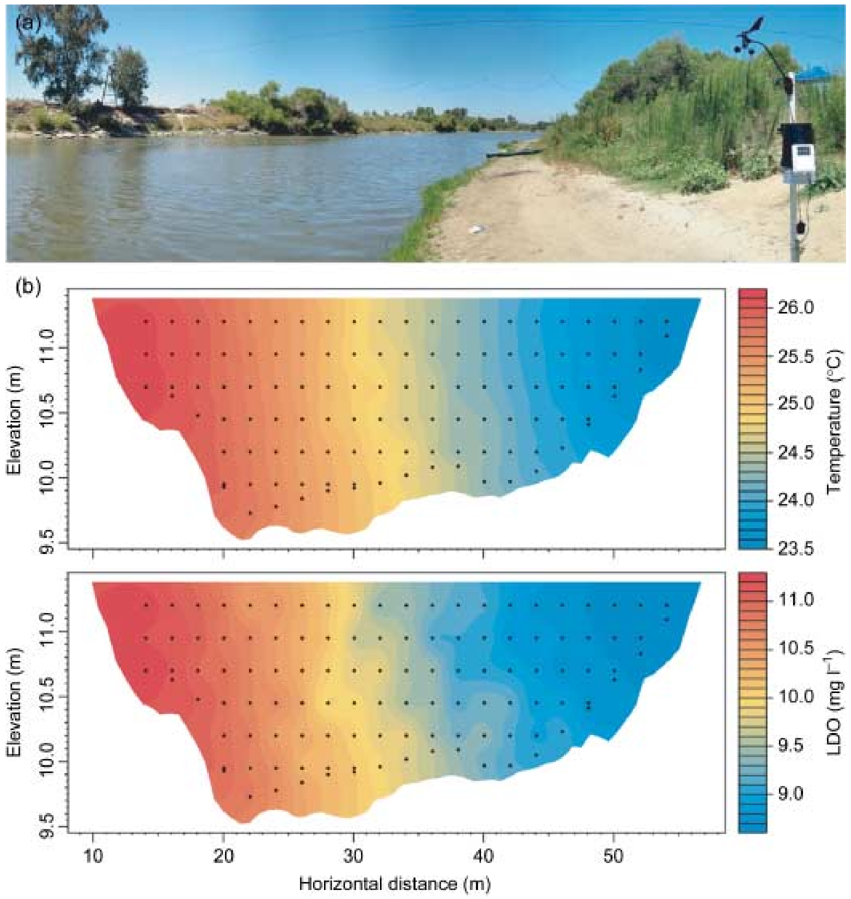

Fig. 7 (a) Networked Info-Mechanical Systems (NIMS) robotic cable system erected on a transect across the San Joaquin River just downstream of its confluence with the Merced River, which enters to the right; (b) significant gradients in temperature and dissolved oxygen (LDO) sampled by sensors conveyed by the NIMS device. The black dots indicate sampling locations.

observe significant horizontal gradients in velocity and water quality (temperature, salinity, DO) within the confluence of two major rivers (Harmon *et al.*, 2007; see Fig. 7). To address three-dimensional space over time, autonomous underwater vehicles (AUVs) have been used extensively by the oceanographic community, and more recently in lakes and river systems (e.g. Laval *et al.*, 2000; Farrell *et al.*, 2005; Sukhatme *et al.*, 2007). These systems can range from powerless drifters, to profiling gliders programmed to regulate their buoyancy to ascend or dive, to fully powered self-propulsion AUVs.

3. Sensor networks in groundwater and the hyporheic zone

Several types of physical and chemical sensor are available in forms suitable for deployment in observation wells or access tubes in the benthic environment. Although they have not yet seen widespread use, such systems would be useful for observing macrophytes, periphyton or other applications in lentic and littoral systems (e.g. Sebestyeni & Schneider, 2004; Westwood *et al.*, 2006; Tremp, 2007). For example, small rugged pressure transducers can be used for mapping the groundwater pressure gradients over broader scales. Basic water quality parameter sensors are also available in compact form, the most common being conductivity and temperature (CT) sensors for observing trends in salinity and temperature; these are also available with integrated pressure transducers to provide the depth of the water column above the sensor (CTD sensors). Several small-diameter, multiparameter water quality sondes similar to those discussed above are also commercially available.

Groundwater pressure gradients are typically modest and difficult to detect at fine spatial scales of interest, say, in the study of macrophytes in a stream segment. For this reason, methods employing arrays of inexpensive temperature sensors have been developed to map temperature gradients in streambeds, and from which groundwater–surface water exchange rates can be estimated (e.g. Johnson *et al.*, 2005; Essaid *et al.*, 2008). Obviously, as chemical sensors, such as for nitrogen, phosphorus and other nutrients, become more accessible in price and size, they will be extremely useful in the observation of groundwater–surface water exchanges and their relation to aquatic plants.

4. Near-future aquatic sensing systems

Major developments in sensor technology are anticipated in the next 5–10 yr in two general areas: novel sensors and integrated, miniaturized sensor systems (i.e. 'lab-on-a-chip'), both of which are expected to increase the functionality and decrease the per-sensor cost. Many of the advancements are anticipated to increase the quality and miniaturization potential for existing physical and chemical sensors (Bobacka *et al.*, 2008; McDonagh *et al.*, 2008). Major innovations, however, are anticipated in the area of biosensor development (i.e. sensor-transducer systems which use biological mechanisms to generate responses associated with targeted pollutants or microorganisms), which is growing exponentially in terms of research papers and patents (Marazuela & Moreno-Bondi, 2002; Rodriguez-Mozaz & Lopes de Alda, 2006; Sassolas *et al.*, 2008; Borisov & Wolfbeis, 2008). Although much of the biosensor field remains in the laboratory validation stage, several commercialization efforts are encouraging in the water quality monitoring area, including a toxicity biosensor for wastewater (Farré *et al.*, 2000), and surface plasmon reflectance (SPR) commercial venture. SPR is an extremely promising optical technique which enables real-time observation of molecular interactions, thus enabling a broad spectrum of biosensing opportunities (for a review, see Homola, 2008).

With these exciting new sensor types comes the rapid development of integrated, miniaturized sensor systems (Joo & Brown, 2008). These systems include not only the sensor-transducer components, but microfluidics, to pretreat samples and add reagents, and the associated circuitry to manage the system in terms of sample throughput, energy management and data communications.

V. Challenges for sensor network development

1. Data collection and management

Sensor deployments can generate far more data than can be managed by the traditional methods used in field research, placing data quality and control beyond the capacity for individuals to effectively monitor. Substantial initial effort and attention to quality assurance/quality control (QA/QC) issues from the outset must be expended to capture, maintain and make high-quality data available for use by others. A large variety of faults can impact on data quality, including sensors affected by aging, biofouling or leaking of internal solutions, or simply sensors with bad connections to the data collection device. Criteria for data integrity vary both by context and by individual, and work on tools and services to capture data, metadata and publications is ongoing (Michener *et al.*, 1997; Borgman *et al.*, 2007; Wallis *et al.*, 2007).

Error checking can occur during or after data have been collected, and indeed may be facilitated by cyberinfrastructure and the incorporation of archived data and sources not in the immediate network. An automated system to perform QA/QC either before or after data are inserted into a database is essential, because of the unwieldy amount of data that can be collected by even a modest sensor network, and some work towards automated fault detection has been made (Sharma *et al.*, 2007). The intercomparison of data from sensors, using Bayesian techniques when multiple sensors of the same type are deployed (Ni & Pottie, 2007), or between sensors and remote sensing data (Grassotti *et al.*, 2003), can be part of data QA. In addition, a model–measurement intercomparison can allow the international scientific community to evaluate the performance of models compared with field observations (Hoffman *et al.*, 2007) to ensure long-term and cross-network comparability.

Systems for managing and making sensor network data accessible include OPeNDAP (www.opendap.org), an open-source project to create a standard Network Data Access Protocol. OPeNDAP also provides software which makes local data accessible to remote locations, regardless of local storage format, facilitating the networking of sensors. In addition, GEON (www.geongrid.org) is a collaboration among a dozen institutions to develop the cyberinfrastructure to support an environment for integrative geoscience research, and EcoGrid (seek.ecoinformatics.org) is a next-generation Internet architecture for data storage, sharing, access and analysis. Work on EcoGrid involves a wide variety of ecological and biodiversity data, and analytical tools for efficiently utilizing data stores to advance ecological and biodiversity science. Although data storage and management in open-source databases, such as MySQL (www.mysql.com), are popular, additional work on publishing and sharing data from MySQL with various users has not been straightforward.

Gaps in the data flow from sensor networks present a widespread and pervasive problem. These gaps may be short-term problems caused by instrument failures, power outages or inclement weather, or more serious long-term gaps (days to weeks) as a result of major instrument problems or maintenance shut-downs. Although many ecologists have the image of perfect fidelity and precision of sensor data, this is far from the truth, even in some of the most sophisticated sensor networks, such as those associated with FLUXNET. Studies have shown that 17–50% or more of individual flux measurements are rejected or missing in such ecosystem studies (Richardson & Hollinger, 2007; Xing *et al.*, 2008). An example of the extent of this problem can be seen in a careful analysis of eddy covariance measurements at the Hesse deciduous forest site in France (Longdoz *et al.*, 2008). Over a full-leaf season, 60% of half-hour values were rejected, with a higher error rate of 69% for night-time measurements (Falge *et al.*, 2001). Even in short-term controlled deployments, sensor networks may fail to record half or even more of the programmed data points (Tolle *et al.*, 2005).

Both short-term and long-term data gaps in ecosystem studies present a serious problem by reducing the quantity and integrity of the sensor outputs and, for long-term deployments, impacting on the accuracy of estimates of ecosystem flux parameters, particularly those related to estimates of net ecosystem productivity, the accuracy of process–climate linkages and the relative source–sink relationships of carbon balance. As a result, there have been a variety of gap-filling methodologies proposed over the past decade, each with their strengths and weaknesses (e.g. Falge *et al.*, 2001; Ruppert *et al.*, 2006; Moffat *et al.*, 2007; Xing *et al.*, 2008).

With the recent developments in cyberinfrastructure, researchers can have near-real time access to all data streams from their sensor networks. This means that instrument failures, power interruptions and even calibration errors can all be quickly identified and corrected, with major data gaps avoided or minimized. Careful attention to system function can enable researchers to reduce the uncertainties in their data collection. A complementary strategy to continuous vigilance of data quality is to have sensor networks designed with redundancy in sensors, data logging devices, and power supplies – in this way, detected hardware failures may be more quickly resolved to minimize data loss. Nevertheless, planned sensor calibration and maintenance schedules to replace hardware before failure are vital to data integrity.

2. Energy efficiency

An issue that cuts across all research domains is that of energy requirements, which defines the limitations of wireless vs. line-powered systems. The design of larger long-term deployments, such as NEON and GLEON, is dependent on the availability of continuous line power. However, wireless sensor networks offer important solutions to issues related to remote and/or short-term deployments (Puccinelli & Haenggi, 2005; Raghunathan *et al.*, 2006), and power management is of most concern in many of the studies involving battery-operated wireless sensor nodes (Raghunathan *et al.*, 2006; Hart & Martinez, 2006; Moraisa *et al.*, 2008; Ruiz-Garcia *et al.*, 2008). In the early days of design considerations for wireless sensor networks, the focus of energy efficiency was on the energy consumed by wireless communication. Although simple and low-rate sensors, such as those typically used for monitoring temperature, humidity, irradiance and wind, require little energy, this is not the case for other sensor modalities, such as those for imaging and acoustic monitoring, which typically require high-rate and high-resolution analog-to-digital (A/D) converters that can be power hungry.

Without continuous battery changes, sensor networks require sophisticated power management techniques coupled to their communications design. The requirement for on-demand high-performance computing and communication for complex information processing, however, can be addressed by new multiprocessor node hardware and software architectures.

Several energy-harvesting techniques are also now feasible, and solar energy harvesting through photovoltaic conversion currently provides the highest power density, making it the method of choice to power sensor nodes (Raghunathan *et al.*, 2006), although less reliable in some ecosystems (Pierce & Elliott, 2008). Alternative energy methods, such as wind and water flow, that supply rechargeable batteries have also been explored for sensor networks (Moraisa *et al.*, 2008).

3. Commercialized sensor network systems

Sensor networks are quickly transitioning from being objects of academic research interest to a technology that is being deployed in a wide variety of applications and is rapidly being commercialized. Several commercial ventures for producing consumer-grade hardware for wireless mesh networks exist, including Crossbow (www.xbow.com), ZigBee (www.zigbee.org) and Sentilla (www.sentilla.com), which all offer various forms of off-the-shelf solutions to wirelessly connected sensors. SensorWare Systems (www.sensorwaresystems.com) is a spin-off company from the NASA/JPL Sensor Webs Project, and thus has benefited from research on *in situ* sensor networks and end-to-end solutions for accessible data flow, in real-time, via the Internet (Delin *et al.*, 2005). Common to all these products is relatively inexpensive commercial technology combined from both the computation and telecommunication industries to create practical, field-deployable and embedded systems.

4. Wireless communication

Standardization is missing at many levels of sensor networks (Hart & Martinez, 2006). Hardware platforms and operating software vary and interoperability is difficult. One way to address standardization issues is through the Institute of Electrical and Electronics Engineers (IEEE) 802.11 family of wireless communication standards. The standards (overlapping significantly with Wi-Fi) are able to handle very high data transmission rates, but are simultaneously power-demanding and face interference problems outside of line-of-sight deployments. In response to power issues related to embedded processors, the IEEE has established a 802.15.4, Wireless Personal Area Network (WPAN) standard for communications, enabling the creation of complex *ad hoc* networks to provide ultra-low power consumption (very long battery life of months or even years) and very short wake-up time capabilities at very low power cost. The WPAN standard assumes that the data transmitted are short and that transmissions occur at a low-duty cycle (active/sleep times ratio), reducing the overall power needs and enabling the application of battery-powered embedded systems (Moraisa *et al.*, 2008). The ZigBee Alliance (www.zigbee.org) set of communication protocols is based on the WPAN standard.

Remote locations are particularly challenging, as the lack of power infrastructure and data communication lines hampers coordinated data collection. A joint NASA–Information Sciences Institute (University of Southern California) project called Sensor Processing and Acquisition Network (SPAN) has established a sensor network with satellite communications to support ecological research (Ye *et al.*, 2008). SPAN relays data from the field from remote locations to the scientist through satellite communication as the wide-area networking (WAN) backhaul.

5. The near-future of sensor networks

One of the benefits of a distributed network is the integration of information obtained from multiple sensors into a larger world view not detectable by any single sensor alone. Going beyond traditional sensor networks and new applications of additional sensor modalities and adaptive sampling, there is now the emergence of a more general notion of model-based active sampling to optimize the sensing process. The key idea is that the system learns spatio-temporal relationships among the measurements made by sensor nodes, and uses this knowledge to optimize the sensing (i.e. whether, when, where and at what fidelity level should a sensor measurement be made) for energy consumption and position of fixed sensors for a required level of overall application-sensing task. The process of learning the spatio-temporal relationships can be based on a variety of approaches: for example, modeling sensors as Gaussian processes and capturing the relationships among them in terms of covariances, or modeling the relationships among sensor values using nonparametric statistical models (Batalin *et al.*, 2004; Schoellhammer, 2008). Common to the different approaches is the ability to predict to some level of confidence the value of a sensor measurement based on sensor measurements at other points in the space–time sensor continuum. Such model-based approaches to sensor data acquisition are in their relative infancy, but promise a general framework to enable the better design and efficiency of sensor networks.

Technological advances in sensors, sensor data logging and communication, and software management of sensor networks will continue to provide transformative potential for new and innovative avenues of ecological research in ways previously not possible. The challenges for the community of ecological researchers, engineers and specialists in software science will be to maintain two-way avenues of communication to continue to design and deploy new technologies for sensor networks. A key step will be the development of programs with field training and sensor network curricula to familiarize the next generation of scientists with these emerging tools.

Acknowledgements

Funding for this work came from the National Science Foundation Cooperative Agreement CCR-0120778 to the Center for Embedded Networked Sensing (CENS) at UCLA and from National Science Foundation Grants No. ANI-00331481 for the development of Networked Infomechanical Systems (NIMS) and EF0410408 for the development of the soil sensors. We thank our many colleagues for their efforts and support that have made this synthesis possible. In particular, Michael Hamilton, Deborah Estrin and William Kaiser have greatly aided our understanding and insights into the application of sensor networks to science-driven ecological questions.

References

Alliance for Coastal Technologies (ACT). 2004. *Performance verification statements for in situ dissolved oxygen sensors ACT VS04-01 through VS04-04*. Solomons, MD, USA: Alliance for Coastal Technologies.

Alliance for Coastal Technologies (ACT). 2006. *Performance verification statements for in situ fluorometers ACT TD06-01 through TD06-08.* Solomons, MD, USA: Alliance for Coastal Technologies.

Alliance for Coastal Technologies (ACT). 2007. *Performance verification statements for in situ turbidity probes ACT VS07-01 through VS07-05.* Solomons, MD, USA: Alliance for Coastal Technologies.

Alliance for Coastal Technologies (ACT). 2008. *Performance verification statements for in situ nutrient analyzers ACT TD08-01 through TD08-04.* Solomons, MD, USA: Alliance for Coastal Technologies.

Allen MF. 1993. Microbial and phosphate dynamics in a restored shrub steppe in southwestern Wyoming. *Restoration Ecology* **1**: 196–205.

Allen MF, Swenson W, Querejeta JI, Egerton-Warburton LM, Treseder KK. 2003. Ecology of mycorrhizae: a conceptual framework for complex interactions among plants and fungi. *Annual Review of Phytopathology* **41**: 271–303.

Allen MF, Vargas R, Graham EA, Swenson W, Hamilton M, Taggart M, Harmon TC, Rat'ko A, Rundel P, Fulkerson B *et al.* 2007. Soil sensor technology: life within a pixel. *Bioscience* **57**: 859–867.

Baldocchi D, Falge E, Gu L, Olson R, Hollinger D, Running S, Anthoni P, Bernhofer C, Davis K, Evans R *et al.* 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. *Bulletin of the American Meteorological Society* **82**: 2415–2434.

Baldocchi DB, Tang J, Xu L. 2006. How switches and lags in biophysical regulators affect spatial–temporal variation of soil respiration in an oak–grass savanna. *Journal of Geophysical Research* **111**: G02008, doi:10.1029/2005JG000063.

Baldocchi DD, Matt DR, Hutchison BA, Mcmillen RT. 1984. Solar-radiation within an oak hickory forest – an evaluation of the extinction coefficients for several radiation components during fully-leafed and leafless periods. *Agricultural and Forest Meteorology* **32**: 307–322.

Baldocchi DD, Verma SB, Anderson DE. 1987. Canopy photosynthesis and water-use efficiency in a deciduous forest *Journal of Applied Ecology* **24**: 251–260.

Batalin M, Sukhatme GS, Yu Y, Rahimi MH, Hansen M, Pottie G, Kaiser K, Estrin D. 2004. *Call and response: experiments in sampling the environment*. Baltimore, MD, USA: ACM SenSys, 25–38.

Beckwith R, Teibel D, Bowen P. 2004. Unwired wine: sensor networks in vineyards. *Proceedings of IEEE Meeting on Sensors* **2**: 561–564.

Bobacka J, Ivaska A, Lewenstam A. 2008. Potentiometric ion sensors. *Chemical Reviews* **108**: 329–351.

Borgman CL, Wallis JC, Mayernik MS, Pepe A. 2007. Drowning in data: digital library architecture to support scientific use of embedded sensor networks. In: *Proceedings of the 7th ACM/IEEE Joint Conference on Digital Libraries*. New York: Association for Computing Machinery, 269–277.

Borisov SM, Wolfbeis OS. 2008. Optical biosensors. *Chemical Reviews* **108**: 423–461.

Bott TL, Newbold JD, Arscott DB. 2006. Ecosystem metabolism in piedmont streams: reach geomorphology modulates the influence of riparian vegetation. *Ecosystems* **9**: 398–421.

Bowen MD, Marques S, Silva LGM, Vono V, Godinho HP. 2006. Comparing on site human and video counts at Igarapava fish ladder, southeastern Brazil. *Neotropical Ichthyology* **4**: 291–294.

Brunt J, Benson B, Vande Castle J, Henshaw D, Porter J. 2007. *LTER Network Cyberinfrastructure Strategic Plan – Version 4*. http://roadrunner.lternet.edu/drupal/?q=node/5.

Burgess SO, Dawson TE. 2008. Using branch and basal sap flow measurements to estimate whole-plant capacitance: a caution. *Plant and Soil* **305**: 5–13.

Burrell J, Brooke T, Beckwith R. 2004. Vineyard computing: sensor networks in agricultural production. *IEEE Pervasive Computing* **3**: 38–45.

Camilli A, Cugnasca CE, Saraiva AM, Hirakawa AR, Corrêa PLP. 2007. From wireless sensors to field mapping: anatomy of an application for precision agriculture. *Computers and Electronics in Agriculture* **58**: 25–36.

Cayan D, VanScoy M, Dettinger M, Helly J. 2003. The wireless watershed at the Santa Margarita Ecological Reserve. *Southwest Hydrology* **2**: 18–19.

Clements, CB, Whiteman CD, Horel JD. 2003. Cold-air-pool structure and evolution in a mountain basin: Peter Sinks, Utah. *Journal of Applied Meteorology* **42**: 752–768.

Cofoot MC, Gilby IC, Wikelski MC, Kays RW. 2008. Interaction location outweighs the competitive advantage of numerical superiority in *Cebus capucinus* intergroup contests *Proceedings of the National Academy of Sciences* **105**: 577–581.

Colangelo DJ. 2007. Response of river metabolism to restoration of flow in the Kissimmee River, Florida, U.S.A. *Freshwater Biology* **52**: 459–470.

Collins SL, Bettencourt LMA, Hagberg A, Brown RF, Moore DI, Bonito G, Delin KA, Jackson SP, Johnson DW, Burleigh SC, Woodrow RR *et al.* 2006. New opportunities in ecological sensing using wireless sensor networks. *Frontiers in Ecology and the Environment* **4**: 402–407.

Coloso JJ, Cole JJ, Hanson PC, Pace ML. 2008. Depth-integrated, continuous estimates of metabolism in a clear-water lake. *Canadian Journal of Fisheries and Aquatic Sciences* **65**: 712–722.

Cooke SJ, Hinch SG, Wikelski M, Andrews RD, Kuchel LJ, Wolcott TG, Butler PJ. 2004. Biotelemetry: a mechanistic approach to ecology. *Trends in Ecology and Evolution* **19**: 334–343.

Daly KL, Byrne RH, Dickson AG, Gallager SM, Perry MJ, Tivey MK. 2004. Chemical and biological sensors for time-series research: current status and new directions. *Marine Technology Society Journal* **38**: 122–144.

Dang T, Bulusu N, Feng W-C, Frolov S, Baptista A. 2007. Adaptive sampling in the Columbia River observation networks. In: *SenSys '07: Proceedings of the 5th International Conference on Embedded Networked Sensor Systems, Sydney, Australia*. New York: Association for Computing Machinery.

Delin K, Jackson SP, Johnson DW, Burleigh SC, Woodrow RR, McAuley JM, Dohm JM, Ip F, Ferre TPA, Rucker DF, Baker VR. 2005. Environmental studies with the sensor web: principles and practice. *Sensors* **5**: 103–117.

Doherty KW, Frye DE, Liberatore SP, Toole JM. 1999. A moored profiling instrument. *Journal of Atmospheric and Oceanic Technology* **16**: 1816–1829.

Dong S, Sprintall J, Gille ST, Talley L. 2008. Southern Ocean mixed-layer depth from Argo float profiles. *Journal Geophysical Research – Oceans* **113** (C6): C060133, doi:10.1029/2006JC004051.

Essaid HI, Zamora CM, McCarthy KA, Vogel JR, Wilson JT. 2008. Using heat to characterize streambed water flux variability in four stream reaches. *Journal of Environmental Quality* **37**: 1010–1023.

Estrin D, Michener W, Bonito G, eds. **2003.** *Environmental cyberinfrastructure needs for distributed sensor networks: a report from a national science foundation sponsored workshop*. La Jolla, CA, USA: Scripps Institution of Oceanography, 12–14 August 2003.

Falge E, Baldocchi D, Olson R, Anthoni P, Aubinet M, Bernhofer C, Burba G, Ceulemans R, Clement R, Dolman H *et al.* 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agricultural and Forest Meteorology* **107**: 43–69.

Falge E, Baldocchi D, Tenhunen J, Aubinet M, Bakwin P, Berbigier P, Bernhofer C, Burba G, Clement R, Davis KJ *et al.* 2002. Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements. *Agricultural and Forest Meteorology* **113**: 53–74.

Farré M, Pasini O, Carmen Alonso M, Castillo M, Barcelo D. 2000. Toxicity assessment of organic pollution in wastewaters using a bacterial biosensor. *Analytica Chimica Acta* **426**: 155–165.

Farrell JA, Pang S, Wei L. 2005. Chemical plume tracing via an autonomous underwater vehicle. *IEEE Journal of Oceanic Engineering* **30**: 428–442.

Forget G, Mercier H, Ferron B. 2008. Combining Argo Profiles with a general circulation model in the North Atlantic. Part 1: realistic transports and improved hydrography, between spring 2002 and spring 2003. *Ocean Modelling* **20**: 17–34.

Gaines SD, Denny MW. 1993. The largest, smallest, highest, lowest, longest, and shortest: extremes in ecology. *Ecology* **74**: 1677–1692.

Gamon JA, Cheng Y, Claudio H, MacKinney L, Sims D. 2006b. A mobile tram system for systematic sampling ecosystem optical properties. *Remote Sensing of Environment* **103**: 246–254

Gamon JA, Rahman AF, Dungan JL, Schildhauer M, Huemmrich KF. 2006a. Spectral Network (SpecNet): what is it and why do we need it? *Remote Sensing of Environment* **103**: 227–235.

Gawne B, Merrick C, Williams DG, Rees G, Oliver R, Bowen PM, Treadwell S, Beattie G, Ellis I, Frankenberg J *et al.* 2007. Patterns of primary and heterotrophic productivity in an arid lowland river. *River Research and Applications* **23**: 1070–1087.

Goldman J, Ramanathan N, Ambrose R, Caron DA, Estrin D, Fisher JC, Gilbert R, Hansen M, Harmon TC, Jay J *et al.* 2007. *Distributed sensing systems for water quality assessment and management*. Washington DC, WA, USA: Woodrow Wilson International Center for Scholars.

Graham EA, Hamilton MP, Mishler BD, Rundel PW, Hansen MH, 2006. Use of a networked digital camera to estimate net CO_2 uptake of a desiccation tolerant moss. *International Journal of Plant Sciences* **167**: 751–758.

Graham EA, Yuen EM, Robertson GF, Kaiser WJ, Hamilton MP, Rundel PW. 2008. Budburst and leaf area expansion measured with a ground-based, mobile camera system and simple color thresholding. *Environmental and Experimental Botany* **65**: 238–244.

Grassotti C, Hoffman RN, Vivoni ER, Entekhabi D. 2003. Multiple-timescale intercomparison of two radar products and rain gauge observations over the Arkansas-Red River basin. *Weather and Forecasting* **18**: 1207–1229.

Gratton G, Donaldson J, Vander Zanden MJ. 2008. Ecosystem linkages between lakes and the surrounding terrestrial landscape in northeast Iceland. *Ecosystems* **11**:5, 764–774.

Gutschick VP, BassiriRad H. 2003. Extreme events as shaping physiology, ecology, and the evolution of plants: toward a unified definition and evaluation of their consequences. *New Phytologist* **160**: 21–42.

Halldin S, Gryning SE, Gottschalk L, Jochum A, Lundin L-C, Van de Griend AA. 1999. Energy, water and carbon exchange in a boreal forest landscape – NOPEX experiences. *Agricultural and Forest Meteorology* **98–99**: 5–29.

Hamilton M., Graham EA, Rundel PW, Allen MF, Kaiser W, Hansen ML, Estrin DL. 2007. New approaches in embedded networked sensing for terrestrial ecological observatories. *Environmental Engineering Science* **24**: 192–204.

Hansen T, Yalamanchili P, Braun H-W. 2002. Wireless measurement and analysis on HPWREN. In: *Proceedings of Passive and Active Measurement Workshop, Fort Collins, CO, USA*. 222–229. http://moat.nlanr.net/Papers/PAM02-meas_HPWREN.pdf

Harmon TC, Ambrose RF, Gilbert RM, Fisher JC, Stealey MJ, Kaiser WJ. 2007. High-resolution river hydraulic and water quality characterization using rapidly deployable Networked Infomechanical Systems (NIMS RD). *Environmental Engineering Science* **24**: 151–159.

Hart JK, Martinez K. 2006. Environmental sensor networks: a revolution in the earth system science? *Earth-Science Reviews* **78**: 177–191

Hestir EL, Khanna S, Andrew ME, Santos MJ, Viers JH, Greenberg JA, Rajapakse SS, Ustin SL. 2008. Identification of invasive vegetation using hyperspectral remote sensing in the California Delta ecosystem. *Remote Sensing of Environment* **112**: 4034–4047.

Hill MJ, Held AA, Leuning R, Coops NC, Hughes D, Cleugh HA. 2006. MODIS spectral signals at a flux tower site: relationships with high-resolution data, and CO_2 flux and light use efficiency measurements. *Remote Sensing of Environment* **103**: 351–368.

Hobbie EA, Wallander H. 2006. Integrating ectomycorrhizal fungi into quantitative frameworks of forest carbon and nitrogen cycling. In: Gadd GM, ed. *Fungi in biogeochemical cycles*. Cambridge, UK: Cambridge University Press, 98–128.

Hoffman FM, Covey CC, Fung IY, Randerson JT, Thornton PE, Lee Y, Rosenbloom NA, Stockli RC, Running SW, Bernholdt DE. 2007. Results from the carbon-land model intercomparison project (C-LAMP) and availability of the data on the earth system grid (ESG). *Journal of Physics Conference Series* **78**: 012026.

Högberg P, Nordgren A, Buchmann N, Taylor AFS, Ekblad A, Hogberg MN, Nyberg G, Ottosson-Lofvenius M, Read DJ. 2001. Large-scale forest girdling shows that current photosynthesis drives soil respiration. *Nature* **411**: 789–792.

Homola J. 2008. Surface plasmon resonance sensors for detection of chemical and biological species. *Chemical Reviews* **108**: 462–493.

Istvánovics V, Honti M, Kovács A, Osztoics A. 2008. Distribution of submerged macrophytes along environmental gradients in large, shallow Lake Balaton (Hungary). *Aquatic Botany*. **88**: 317–330.

Jarvis PG. 1989. Atmospheric carbon-dioxide and forests. *Philosophical Transactions of the Royal Society of London, Series B – Biological Sciences* **324**: 369–392.

Johnson AN, Boer BR, Woessner WW, Stanford JA, Poole GC, Thomas SA, O'Daniel SJ. 2005. Evaluation of an inexpensive small-diameter temperature logger for documenting ground water–river interactions. *Ground Water Monitoring and Remediation* **25**: 68–74.

Johnson D, Leake JR, Read DJ. 2006. Role of arbuscular mycorrhizal fungi in carbon and nutrient cycling in grassland. In: Gadd GM, ed. *Fungi in biogeochemical cycles*. Cambridge, UK: Cambridge University Press, 129–150.

Johnson KS, Coletti LJ. 2002. *In situ* ultraviolet spectrophotometry for high resolution and long term monitoring of nitrate, bromide and bisulfide in the ocean. *Deep-Sea Research I* **49**: 1291–1305.

Johnson KS, Needoba JA, Riser SC, Showers WJ. 2007. Chemical sensor networks for the aquatic environment. *Chemical Reviews* **107**: 623–640.

Johnson RK, Furse MT, Hering D, Sa L. 2007. Ecological relationships between stream communities and spatial scale: implications for designing catchment level monitoring programmes. *Freshwater Biology* **52**: 939–958.

Joo S, Brown, RB. 2008. Chemical sensors with integrated electronics. *Chemical Reviews* **108**: 638–651.

Jordan BL, Batalin MA, Kaiser WJ. 2007. NIMS RD: a rapidly deployable cable-based robot. In: *IEEE International Conference on Robotics and Automation, Rome, Italy, 10–14 April 2007*. Rome, 144–150. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=4209083&isnumber=4209049

Juang P, Oki H, Wang Y. 2002. Energy-efficient computing for wildlife tracking: design tradeoffs and early experiences with ZebraNet. In: *Proceedings of the 10th Annual Conference on Architectural Support for Programming Languages and Operating Systems* **30**: 96–107. http://www.princeton.edu/~peh/publications/znet.pdf

Keller M, Schimel DS, Hargrove WW, Hoffman FM. 2008. A continental strategy for the National Ecological Observatory Network. *Frontiers in Ecology and the Environment* **6**: 282–284.

Klironomos JN, Rillig MC, Allen MF. 1999. Designing belowground field experiments with the help of semi-variance and power analyses. *Applied Soil Ecology* **12**: 227–238.

Laffea L, Monson R, Manning R, Han A, Glasser S, Oncley J, Sun J, Burns S, Semmer S, Militzer J. 2006. Comprehensive monitoring of CO_2 sequestration in subalpine forest ecosystems and its relation to global warming. *ACM SenSys 2006*. New York: Association for Computing Machinery, 423–424.

Laval B, Bird JS, Helland, PD. 2000. An autonomous underwater vehicle for the study of small lakes. *Journal of Atmospheric and Oceanic Technology* **17**: 69–76.

Le Goff T, Braven J, Ebdon L, Scholefield D. 2003. Automatic continuous river monitoring of nitrate using a novel ion-selective electrode. *Journal of Environmental Monitoring* **5**: 353–358.

Levine SA. 1992. The problem of pattern and scale in ecology: the Robert H. MacArthur award lecture. *Ecology* **73**: 1943–1967.

Ley TW, Muzzy AS. 1992. Experiences with an RF telemetry based automated weather station network in Washington State. *American Society of Agricultural Engineering Paper* **92-2144**.

Longdoz B, Gross P, Granier A. 2008. Multiple quality tests for analyzing CO_2 fluxes in a beech temperate forest *Biogeosciences* **5**: 719–729

Marazuela MD, Moreno-Bondi MC. 2002. Fiber-optic biosensors – an overview. *Analytical & Bioanalytical Chemistry* **372**: 664–682.

McDonagh C, Burke CS, MacCraith BD. 2008. Optical chemical sensors. *Chemical Reviews* **108**: 400–422.

Michener WK, Brunt JW, Helly J, Kirchner TB, Stafford SG. 1997. Nongeospatial metadata for ecology. *Ecological Applications* **7**: 330–342.

Misson L, Baldocchi DD, Black TA, Blanken PD, Brunet Y, Yuste JC, Dorsey JR, Falk M, Granier A, Irvine MR *et al.* 2007. Partitioning forest carbon fluxes with overstory and understory eddy-covariance measurements: a synthesis based on FLUXNET data. *Agricultural and Forest Meteorology* **144**: 14–31.

Moffat AM, Papale D, Reichstein M, Hollinger DY, Richardson AD, Barr AG, Beckstein C, Braswell BH, Churkina G, Desai AR *et al.* 2007. Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes. *Agricultural and Forest Meteorology* **147**: 209–232.

Montgomery JL, Harmon T, Haas CN, Hooper R, Clesceri NL, Graham W, Kaiser W, Sanderson A, Minsker B, Schnoor J *et al.* 2007. The WATERS Network: an integrated environmental observatory network for water research. *Environmental Science & Technology* **41**: 6642–6647.

Moraisa R, Fernandes MA, Matos SG, Serôdio C, Ferreira PJSG, Reis MJCS. 2008. A ZigBee multi-powered wireless acquisition device for remote sensing applications in precision viticulture. *Computers and Electronics in Agriculture* **62**: 94–106.

Ni K, Pottie G. 2007. Bayesian selection of nonfaulty sensors. In: *IEEE International Symposium on Information Theory, 24–29 June 2007*. Nice, Frrance, 616–620. http://comelec.enst.fr/~belfiore/CD_ISIT/pdfs/616.pdf

Olson RJ, Sosik HM. 2007. A submersible imaging-in-flow instrument to analyze nano- and microplankton: imaging FlowCytobot. *Limnology and Oceanography: Methods* **5**: 195–203.

Pierce FJ, Elliott TV. 2008. Regional and on-farm wireless sensor networks for agricultural systems in Eastern Washington. *Computers and Electronics in Agriculture* **61**: 32–43.

Polastre J, Szewczyk R, Mainwaring A, Culler D, Anderson J. 2004. Analysis of wireless sensor networks for habitat monitoring. In: Raghavendra CS, Sivalingam KM, Znati T, eds. *Wireless sensor networks*. Berlin, Germany: Springer-Verlag, 399–423.

Porter J, Arzberger P, Hanson PC, Kratz TK, Gage S, Williams T, Shapiro S, Bryant P, Lin F, King H *et al.* 2005. Wireless sensor networks for ecology. *BioScience* **55**: 561–572.

Prien RD. 2007. The future of chemical *in situ* sensors. *Marine Chemistry* **107**: 422–432.

Puccinelli D, Haenggi H. 2005. Wireless sensor networks: applications and challenges of ubiquitous sensing. *IEEE Circuits and Systems Magazine* **2005** (3): 19–29.

Raghunathan N, Balzano L, Burt M, Estrin D, Harmon T, Harvey C, Jay J, Kohler E, Rothenberg S, Srivastava M. 2006. Rapid deployment with confidence: calibration and fault detection in environmental sensor networks. Center for Embedded Network Sensing, Technical Reports. Paper 10. <http://repositories.cdlib.org/cens/techrep/10>

Rahimi M, Pon R, Kaiser WJ, Sukhatme GS, Estrin D, Srivastavan M. 2004. Adaptive sampling for environmental robotics. In: *IEEE International Conference on Intelligent Robots and Systems* 4: 3537–3544.

Reichstein M, Falge E, Baldocchi D, Papale D, Aubinet M, Berbigier P, Bernhofer C, Buchmann N, Gilmanov T, Granier A *et al.* 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. *Global Change Biology* **11**: 1424–1439.

Reynolds-Fleming JV, Fleming JG, Luettich RA. 2002. Portable autonomous vertical profiler for estuarine applications. *Estuaries* **25**: 142–147.

Richardson AD, Hollinger DY. 2007. A method to estimate the additional uncertainty in gap-filled NEE resulting from long gaps in the CO_2 flux record. *Agricultural and Forest Meteorology* **147**: 719–729.

Richardson AD, Jenkins JP, Braswell BH, Hollinger DY, Ollinger SV, Smith M-L. 2007. Use of digital webcam images to track spring green-up in a deciduous broadleaf forest. *Oecologia* **152**: 323–334.

Rodriguez-Mozaz S, Lopes de Alda MJ. 2006. Biosenors as useful tools for environmental analysis and monitoring. *Analytical & Bioanalytical Chemistry* **386**: 1025–1041.

Ruiz-Garcia L, Barreiro P, Robla JI. 2008. Performance of ZigBee-based wireless sensor nodes for real-time monitoring of fruit logistics. *Journal of Food Engineering* **87**: 405–415

Running SW, Baldocchi DD, Turner DP, Gower ST, Bakwin PS, Hibbard KA. 1999. A global terrestrial monitoring network integrating tower fluxes, flask sampling, ecosystem modeling and EOS satellite data. *Remote Sensing of the Environment* **70**: 108–127.

Ruppert J, Mauder M, Thomas C, Lüers J. 2006. Innovative gap-filling strategy for annual sums of CO_2 net ecosystem exchange. *Agricultural and Forest Meteorology* **138**: 5–18.

Sassolas A, Leca-Bouvier BD, Blum LJ. 2008. DNA biosensors and microarrays. *Chemical Reviews* **108**: 109–139.

Schoellhammer TA. 2008. *Tools for distributed sensing system design, deployment and maintenance with applications to soil monitoring.* PhD dissertation, Los Angeles, CA, USA: University of California.

Scholefield D, Le Goff T, Braven J, Ebdonb L, Longc, T, Butlera M. 2005. Concerted diurnal patterns in riverine nutrient concentrations and physical conditions. *Science of the Total Environment* **344**: 201–210.

Sebestyeni SD, Schneider RL. 2004. Seepage patterns, pore water, and aquatic plants: hydrological and biogeochemical relationships in lakes. *Biogeochemistry* **68**: 383–409.

Seeger M. 2004. Gaussian processes for machine learning. *International Journal of Neural Systems* **14**: 69–106.

Sellers PJ, Hall FG, Kelly RD, Black A, Baldocchi D, Berry J, Ryan M, Ranson KJ, Crill PM, Lettenmaier DP *et al.* 1997. BOREAS in 1997: scientific results, experimental overview and future directions. *Journal of Geophysical Research* **102**: 28 731–28 770.

Sharma A, Golubchik L, Govindan R. 2007. On the prevalence of sensor faults in real-world deployments. In: *4th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, 18–21 June, 2007*. San Diego, USA, 213–222. http://cchen1.csie.ntust.edu.tw/students/2009/On%20the%20Prevalence%20of%20Sensor%20Faults%20in%20Real%20World%20Deployments.pdf

Singh A, Krause A, Guestrin C, Kaiser WJ, Batalin M. 2007. Efficient planning of informative paths for multiple robots. In: *Proceedings of the International Joint Conference on Artificial Intelligence*. Hyderabad, India, 2204–2211. http://www.aaai.org/Papers/IJCAI/2007/IJCAI07-355.pdf

Slaughter DC, Giles DK, Downey D. 2008. Autonomous robotic weed control systems: a review. *Computers and Electronics in Agriculture* **61**: 63–78.

Sosik HM, Olson RJ. 2007. Automated taxonomic classification of phytoplankton sampled with imaging-in-flow cytometry. *Limnology and Oceanography: Methods* **5**: 204–216.

Stewart AM, Frank DA. 2008. Short sampling intervals reveal very rapid root turnover in a temperate grassland. *Oecologia* **157**: 453–458.

Stover DB, Day FP, Butnor JR, Drake BG. 2007. Effect of elevated CO_2 on coarse-root biomass in Florida scrub detected by ground-penetrating radar. *Ecology* **88**: 1328–1334.

Sukhatme GS, Dhariwal A, Zhang B, Oberg C, Stauffer B, Caron DA. 2007. Design and development of a wireless robotic networked aquatic microbial observing system. *Environmental Engineering Science* **24**: 205–215.

Tang J, Baldocchi DB. 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**: 183–207.

Tang J, Baldocchi DD, Xu L. 2005. Tree photosynthesis modulates soil respiration in a savanna ecosystem. *Global Change Biology* **11**: 1298–1304

Tengberg A, Hovdenes J, Andersson JH, Brocandel O, Diaz R, Hebert D, Arnerich T, Huber C, Körtzinger A, Khripounoff A *et al.* 2006. Evaluation of a lifetime-based optode to measure oxygen in aquatic systems. *Limnological and Oceanographic Methods* **4**: 7–17.

Tolle G, Polastre J, Szewczyk R, Culler D, Turner N, Tu K, Burgess S, Dawson T, Buonadonna P, Gay D *et al.* 2005. A macroscope in the redwoods. In: *ACM SenSys 2005, San Diego, CA*. New York: Association for Computing Machinery, 51–63.

Tremp H. 2007. Spatial and environmental effects on hydrophytic macrophyte occurrence in the Upper Rhine floodplain (Germany). *Hydrobiologia* **586**: 167–177.

Turner DP, Ritts WD, Cohen WB, Maeirsperger TK, Gower ST, Kirschbaum AA, Running SW, Zhao MS, Wofsy SC, Dunn AL *et al.* 2005. Site-level evaluation of satellite-based global terrestrial gross primary production and net primary production monitoring. *Global Change Biology* **11**: 666–684.

Ustin SL, Roberts DA, Gamon JA, Asner GP, Green RO. 2004. Using imaging spectroscopy to study ecosystem processes and properties. *BioScience* **54**: 523–533.

Vargas R, Allen MF. 2008a. Dynamics of fine roots, fungal rhizomorphs and soil respiration in a mixed temperate forest: integrating sensors and observations. *Vadose Zone Journal* **7**: 1055–1064.

Vargas R, Allen MF. 2008b. Environmental controls and the influence of vegetation type, fine roots and rhizomorphs on diel and seasonal variation in soil respiration. *New Phytologist* **179**: 460–471.

Vargas R, Allen MF. 2008c. Diel patterns of soil respiration in a tropical forest after Hurricane Wilma. *Journal of Geophysical Research* **113**: G03021.

Vermetten AWM, Ganzeveld ML, Jeuken A, Hofschreuder P, Mohren GMJ. 1994. CO_2 uptake by a stand of Douglas fir: flux measurements compared with model calculations. *Agricultural and Forest Meteorology* **72**: 57–80.

Verstraeten WW, Veroustraete F, Feyen J. 2008. Assessment of evapotranspiration and soil moisture content across different scales of observation. *Sensors* **8**: 70–117.

Wallis JC, Borgman CL, Mayernik MS, Pepe A, Ramanathan N, Hansen M. 2007. Know thy sensor: trust, data quality, and data integrity in scientific digital libraries, In: Kovacs L, Fuhr N, Meghini C, eds. *Lecture notes in computer science: research and advanced technology for digital libraries*, Berlin, Germany: Springer, 380–391.

Westwood CG, Teeuw RM, Wade PM, Holmes NTH, Guyard P. 2006. Influences of environmental conditions on macrophyte communities in drought-affected headwater streams. *River Research and Applications*. **23**: 1070–1087.

Wikelski M, Kays RW, Kasdin NJ, Thorup K, Smith JA, Swenson GW. 2007. Going wild: what a global small-animal tracking system could do for experimental biologists *Journal of Experimental Biology* **210**: 181–186.

Wofsy SC, Goulden ML, Munger JW, Fan SM, Bakwin PS, Daube BC, Bassow SL, Bazzaz FA. 1993. Net exchange of CO_2 in a mid-latitude forest. *Science* **260**: 1314–1317

Xing ZS, Bourque CPA, Meng FR, Cox RM, Swift DE, Zha TS, Chow L. 2008. A process-based model designed for filling of large data gaps in tower-based measurements of net ecosystem productivity. *Ecological Modelling* **213**: 165–179.

Ye W, Silva F, DeSchon A, Bhatt S. 2008. Architecture of a satellite-based sensor network for environment observation. In: *NASA Earth Science Technology Conference (ESTC2008), Adelphi, MD, June 24–26, 2008*. California, USA. University of Southern California, Information Sciences Institute: http://www.esto.nasa.gov/conferences/estc2008/papers/Ye_Wei_A8P2.pdf