New Eyes on the World: Advanced Sensors for Ecology

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Innovative uses of advanced sensors and sensor networks are starting to be translated into new ecological knowledge. These sensors are providing a new set of "eyes" through which researchers may observe the world in new ways, extend spatial and temporal scales of observation, more accurately estimate what cannot be observed, and, most important, obtain unexpected results or develop new paradigms. Automated sensors are widely deployed by members of the Organization of Biological Field Stations, yet some needs—particularly for chemical and biological sensors—are not currently being met. There are additional opportunities for developing sensor networks at synoptic, regional, continental, and global scales. Although we are seeing more uses of sensor systems and, in particular, sensor networks, the opportunities for these systems are just beginning to be realized, with much more work to be done, including formulation of new questions, development of new sensors, better software, and new ways for researchers to work together across large distances.

Keywords: sensors, Organization of Biological Field Stations, sensor networks, environmental monitoring

Technological advances in cyberinfrastructure, such as computers, nanotechnology, communications, and networking, have broad impacts on almost every aspect of modern life. In field biology, ecology, and environmental science, this revolution has been embodied in the availability of new field sensors and sensor systems that hold the promise of unprecedented access to information about the environment (box 1; Cayan et al. 2003, Estrin et al. 2003, Vernon et al. 2003, Beeby et al. 2004, Daly et al. 2004, Collins et al. 2006, Hart and Martinez 2006, Hamilton et al. 2007, Johnson et al. 2007). Automated buoys in remote lakes can report on the real-time impacts of typhoons on lake structure and biology (Porter et al. 2005, Hanson 2007, Jones et al. 2008), and animal-tracking networks can provide real-time locations for dozens of animals simultaneously (Aliaga-Rossel et al. 2006).

Growing use of sensor systems depends on development of new types of sensors, new ways of recording and processing the data they collect, and new ways of communicating that information. Field biologists' adoption of advanced sensor systems has been driven by scientific imperatives, particularly the need for data at high frequencies, and facilitated by decreasing costs. In this article, sensor systems are defined as technological systems that replace, augment, or surpass human observers of ecological phenomena. Sensor systems can be found in both monitoring and experimental applications. They are typically characterized by either greater frequency of measurements or greater spatial dispersion than is possible through human observation. Some systems are passive in that they measure but do not manipulate or otherwise respond to their environment, whereas other advanced sensor systems can actively respond to environmental changes or even perform experimental manipulations. The impact of sensor systems is not limited to biology and ecology. Hart and Martinez (2006) reviewed more than 50 examples of the use of advanced sensor applications in earth system science, concluding that sensor networks "will become a standard research tool."

Automated sensor systems can extend the scales of observations to make them better coincide with theories and models. Biological and ecological research rests on the pillars of observations, theories, and models. Progress is most easily made when temporal, spatial, and quantitative scales are comparable. That is, if regional-scale theory focuses on time scales of years to decades, but models are built on data from monthly observations at a few sites, it can be difficult to connect the two. In contrast, when theories and models can make testable predictions using the same measurement frequency and spatial extent as the observations, understanding of processes is enhanced. Advanced sensor systems hold the promise of allowing researchers to extend spatial and temporal scales of observation, thus permitting a wider array of theories and models to be tested.

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Box 1. Primer on advanced sensor systems.

The confluence of advances in sensor hardware and intelligence, networking, and data integration has led to advanced sensor systems that have allowed ecologists to make measurements that were previously impossible or prohibitively expensive. Before the 1980s, a scientist making *in situ* measurements might deploy a series of sensors such as a maximum/minimum thermometer, a recording hygrometer, or a precipitation collector, and then visit the instruments periodically to record the data manually, as in the photograph on the right. With the advent of microprocessors in the 1980s and 1990s, sensors were often connected to a data logger that not only increased the frequency with which measurements could be made but also stored the data electronically. The data were then retrieved periodically during visits to the instruments. At that time, some data loggers were connected to telephone wires or power-hungry VHF radio modems, allowing automated retrieval of data, albeit at low speeds. However, in the past several years the combination of four technological developments has led to greatly enhanced capabilities for using *in situ* sensing of the environment to draw ecological inferences.

A monitoring station on Niwot Ridge in 1953 required hazardous and difficult manual visits. Photograph: John Marr (provided by the Niwot Ridge Long-Term Ecological Research project).

New sensing technologies. Ecologists are no longer restricted to measuring only a few variables, such as meteorological variables, stream flow, or soil temperatures. Advances in sensor technology driven by concomitant advances in nanotechnology, materials technology, chemistry, and optics now let ecologists make measurements of variables such as carbon dioxide *in situ* in air, water, and soil; the concentration of algal pigments in water bodies; soil moisture; concentrations of various chemical species such as hydrogen ions, oxygen, nutrients, ions and contaminants; and movement of organisms (Daly et al. 2004, Goldman et al. 2007, Johnson et al. 2007). Often these measurements can be made with tiny instruments at high sensitivity using low power. Although many of these new sensors need to be additionally field-hardened, ecologists now have an ever-growing number of tools in their field observation toolbox.

Intelligent sensors and sensor nodes. Embedding microprocessors and wireless communication with sensors gives sensor nodes the capacity to preprocess data collected by multiple sensors within a network. This preprocessing can include checking the data quality of individual sensors by comparing concurrent readings from nearby sensors and computing data summaries across all sensors in the network to be communicated, in addition to the raw data, directly to the ecologist (Estrin et al. 2003, Yao K. et al. 2003, Collins et al. 2006). Intelligent sensors can also be used to adapt sampling frequencies to current environmental conditions. Thus Web cameras can use movement detection to send images only when organisms move, or rain intensity need only be reported when it is actually raining.

Improved networking and communications. Improvements in networking and communications, such as the advent of low-power, high-bandwidth digital spread-spectrum radios, increasingly ubiquitous cell phone coverage, and satellite relays have allowed ecologists to communicate with sensors in real time over large distances. The speed with which data can be accessed allows the operation of bandwidth-hungry sensors such as video cameras, flux towers or sound sensors, more widely distributed sensors, and even improved data quality, as problems can be detected immediately and addressed (Delin 2002, Vernon et al. 2003, Yao K. et al. 2003, Szewczyk et al. 2004, Porter et al. 2005, Collins et al. 2006, Hart and Martinez 2006, Tilak et al. 2007).

Improved data integration technology. Ecologists have a growing array of tools for processing information, including databases, statistical languages, metadata editors, and scientific workflow tools. Streaming data from sensors demands approaches that go well beyond a spreadsheet. Software that allows retrieval and analysis of sensor data collected from a variety of sources makes "drinking from the firehose" of environmental data possible. For example, it is now possible to collect real-time data from multiple locations around the world with just a few keystrokes, making the ever-growing mass of data from environmental sensors available to individual scientists for analysis and synthesis.

However, sensor systems are not suitable for everyone or every situation. As systems increase in complexity, they may require considerable collaboration among technicians, programmers and ecologists, and field biologists. Technical expertise is needed to deploy, operate, and maintain sensor systems, and this technical training is outside the curricula for most field biologists. In most cases, sensor systems are not "plug and play." Installation, wiring, trouble-shooting, programming, quality assurance and quality control protocols, data-management systems, and data-harvesting routines can be challenging to design, develop, and implement. Sensors themselves are often far from perfect. Even sensors that measure routine parameters such as soil moisture or temperature can fail for a variety of reasons (Daly et al. 2004). Many sensors are developed and tested in relatively benign conditions, then challenged through use in particularly harsh environments such as boreal forests, salt marshes, or desert soils. For these reasons, not all technological advances necessarily translate into new biological, ecological, or environmental knowledge. Mismatches between what the technology can provide and what information is needed by researchers pose additional challenges.

Here we seek to identify advances in ecological knowledge that have come about through the application of advanced sensors and sensor networks and to evaluate the level of use of advanced sensors at biological field stations. We focus our examination of the role of advanced sensors in ecological research around two questions: Is the promise of advanced sensors being translated into new ecological knowledge and insights, and if so, how? What types of advanced sensor technology are actually deployed and in use at biological field stations and marine labs, and what types of advances are needed to meet future needs?

The first question focuses primarily on advanced applications of sensors and on how sensors are being used to extend observations of ecological phenomena and can be used to accurately estimate ecological properties that cannot be measured directly. Especially important are cases in which the use of advanced sensors has led to new ways of thinking about ecological systems, extending our understanding rather than filling data gaps in our existing paradigms. The second question concerns the adoption of advanced sensor systems by field biologists at biological field stations and marine laboratories. We focus on biological field stations and marine labs because they are frequently hubs of collaboration that provide access to novel, remote, diverse, and challenging environments, while providing infrastructure to support field biology. In this context they are a logical place to examine the state of the art for working field biologists and to examine trends in the use of sensor technologies.

Uses of advanced sensors

Advanced sensor networks have great potential for advancing ecological understanding (box 1). Sensor networks can extend our ability to observe ecological phenomena by allowing us to record observations with much greater frequency and at larger spatial extents than would be possible through manual observation alone. Sensor networks allow us to observe where we cannot physically be—an advantage proved invaluable in studying oceans, animal behavior, or rare and dangerous events. In other cases, sensor networks coupled with models allow us to estimate rates of ecosystem processes that simply cannot be observed directly. Because sensor networks allow us to make observations unobtrusively at unprecedented temporal and spatial scales, it is likely that we will observe new, unexpected phenomena. In the following illustrative examples, ranging from studies of nesting success to ocean currents to ecosystem metabolism, we show new biological and ecological insights that resulted from the application of advanced sensor systems (table 1).

The field biologist's "eyes"

> *You can imagine how much you'd miss if you only had your eyes open one day a month every year. That was the amount of data we were collecting. I see a very different vision now. I see a vision of having these sensors deployed so we are going to have our eyes open 24/7/365, and that will revolutionize what we understand.*
>
> —Hilary Swain, Archbold Biological Station, 2008

Direct observation of plants and animals is a hallmark of the naturalist's approach to studying ecosystems. The advent of affordable digital photography has made documentation of these types of observations accessible to all ecologists. However, a new level of science has emerged from technologies that not only capture the images but also transmit, store, and analyze them. These advances allow the ecosystem to be "seen" or "heard" even though a researcher is not present.

The study of nesting success in birds is one example of research that uses automated observing systems. These types of studies have traditionally required repeated, manual observations of nests, greatly limiting the number of nests an individual researcher could monitor. In contrast, the deployment of video recording equipment and digital Webcams can produce detailed records of chick survival and feeding over a broad geographic scale. Bryan Watts and his colleagues at the Center for Conservation Biology at the College of William and Mary in Virginia used a network of video recorders to simultaneously monitor 18 bald eagle (*Haliaeetus leucocephalus*) nests (figure 1e) to study the effects of salinity on diet and chick provisioning (Markham and Watts 2008). The level of coverage possible with this approach allowed the discovery of rare behaviors such as cannibalism, which would not likely be observed with the limited coverage of traditional studies (Markham and Watts 2007).

Such uses of automated imaging are not confined to the terrestrial environment. Interactions between fish at night are ecologically important in coral reef ecosystems, but human observers cannot document them in person because the required lights and the looming presence of the researcher would disturb the very behaviors researchers seek to observe. However, Holbrook and Schmitt (1997, 1999, 2002) used networks of video cameras with infrared illumination, which is invisible to fish, to allow unobtrusive nighttime monitoring. They were able to observe for the first time the nocturnal settlement of late-stage larvae of damselfishes in specific microhabitats. They were also able to document that competition for predator-free space was the mechanism responsible for the observed density-dependent population dynamics on the reef. They found that the vast majority of mortality of early postsettlement fish occurs at night, when they become vulnerable to predators because of intra- or interspecific aggression.

Collecting images is not the only way to observe animal behavior. An animal's physiological condition and move-

Table 1. Summary of examples of advanced sensor use resulting in ecological, biological, and environmental insights.

Example	Sensor technology	Sensor roles	Ecological, biological, and environmental insights
Eagle nesting (Watts et al. 2006, Markham and Watts 2007, 2008)	Video capture	C, A, B	Effects of salinity on diet and chick provisioning, occurrence of cannibalism
Moorea Coral Reef (Holbrook and Schmitt 1997, 1999, 2002)	Underwater infrared video	C, A, B	Competition for predator-free space leads to density-dependent population dynamics
Animals on Barro Colorado Island (Aliaga-Rossel et al. 2006, Crofoot et al. 2008)	Automated radio tracking	A, B, D	Location-specific dominance relations in monkeys, unexpected predation
California current system (Davis et al. 2008)	Robotic glider	B, A, E, D	Abrupt oceanic fronts found in a transect more than 400 kilometers in length
Lake remediation (Denkenberger et al. 2006, Effler et al. 2006)	Robotic water quality monitors	A, E, D	Detailed measures of water quality in target and reference lakes shared with the public in near-real time
Desert shrub microclimate (Collins et al. 2006)	Network of temperature sensors	A, B, D	Species-specific microclimate associations for shrubs, improved data quality
Lake processes (Kratz et al. 2006, Pan et al. 2006)	Networked, automated buoys	D, A, B	"Now casting"/modeling with sensor data; coupling lake circulation and metabolism models
Atmospheric fluxes (FLUXNET) (Kurc and Small 2004, Misson et al. 2007)	Computerized multisensor measurement systems	A, B	Short-term variations in soil carbon dioxide (CO_2) fluxes in relation to key environmental drivers such as soil water content and temperature
"River of air" (Pypker et al. 2007a, 2007b)	Network of meteorological stations	A, B	"River of air" used to assess CO_2 fluxes in a forest environment
Soundscapes (Gage 2003, Krause and Gage 2003)	Network of audio sensors	A, B, D	Sound as indicators of habitat quality, species arrival time, individual species identifications

Note: The sensor roles include five reasons for using wireless sensors (Porter et al. 2005): A = high frequency of observation, B = observations over wide areas, C = unobtrusive observation, D = real time data, and E = bidirectional communication (allowing control). Sensor roles are ordered by their relative importance.

ment can provide invaluable information on a species' ecology. For example, on Barro Colorado Island in Panama, an automated radio telemetry system, consisting of a wirelessly networked system of seven automated directional receivers on 40-meter (m)-tall towers, provides bearings every 10 seconds for tracking radio-tagged rainforest animals. Roland Kays, Martin Wikelski, and their collaborators have used the system to track daily activity patterns in a variety of tropical species, including agoutis (*Dasyprocta punctata*) and their major predator, ocelots (*Leopardus pardalis*), and to detect the time and location of kills (Aliaga-Rossel et al. 2006). Not until the automated radio tracking system was used in a study of intergroup interactions among capuchin monkeys (*Cebus capucinus*) was it possible to collect adequate data on how contest location and group size interacted to shape relationships among groups. With the system, however, researchers were able to use 71,870 locations to determine that although larger groups tended to win contests, they were less likely to do so as they approached the center of the territory of the smaller group (Crofoot et al. 2008).

Extending spatial and temporal scales

Sensor networks have pushed observations to a new domain in which data are collected at high frequencies (up to several times per second) over extended spatial extents, requiring researchers to explore new ways of modeling ecosystems and challenging them to identify the most compelling scientific questions, given these new data. Sometimes covering space demands that sensors move in three dimensions through the environment. Mark Ohman and Russ Davis, of the California Current Ecosystem Long-Term Ecological Research (LTER) project, are using robotic ocean gliders in their research (figure 1b). These undersea gliders were developed in the Davis lab at the Scripps Institution of Oceanography (Sherman et al. 2001). Gliders follow a cycle, diving to depths of 500 to 1000 m and recording physical (conductivity, temperature, density) and biological (chlorophyll *a* and acoustic backscatter) properties of the water, then return to the surface and use the global positioning system to establish the glider's location, transmit data from the dive directly to researchers using the Iridium satellite phone network, and receive new commands. Over the course of a deployment lasting longer than three months, one glider can repeatedly sample a transect more than 400 kilometers in length. Gliders have allowed researchers to fill in the long temporal gaps between research cruises to resolve the mechanisms leading to low-frequency variations in the pelagic ecosystem, and to detect development of hitherto unanticipated coastal circulation features. Recently, the gliders have revealed abrupt oceanic fronts—sharp spatial gradients in both physical and biological characteristics of the water column (figure 2)—that may be particularly important for pelagic predator-prey interactions (Davis et al. 2008).

In complex and dynamic ecosystems such as lakes, high-frequency vertical measurements allow researchers to better understand the consequences of environmental degradation.

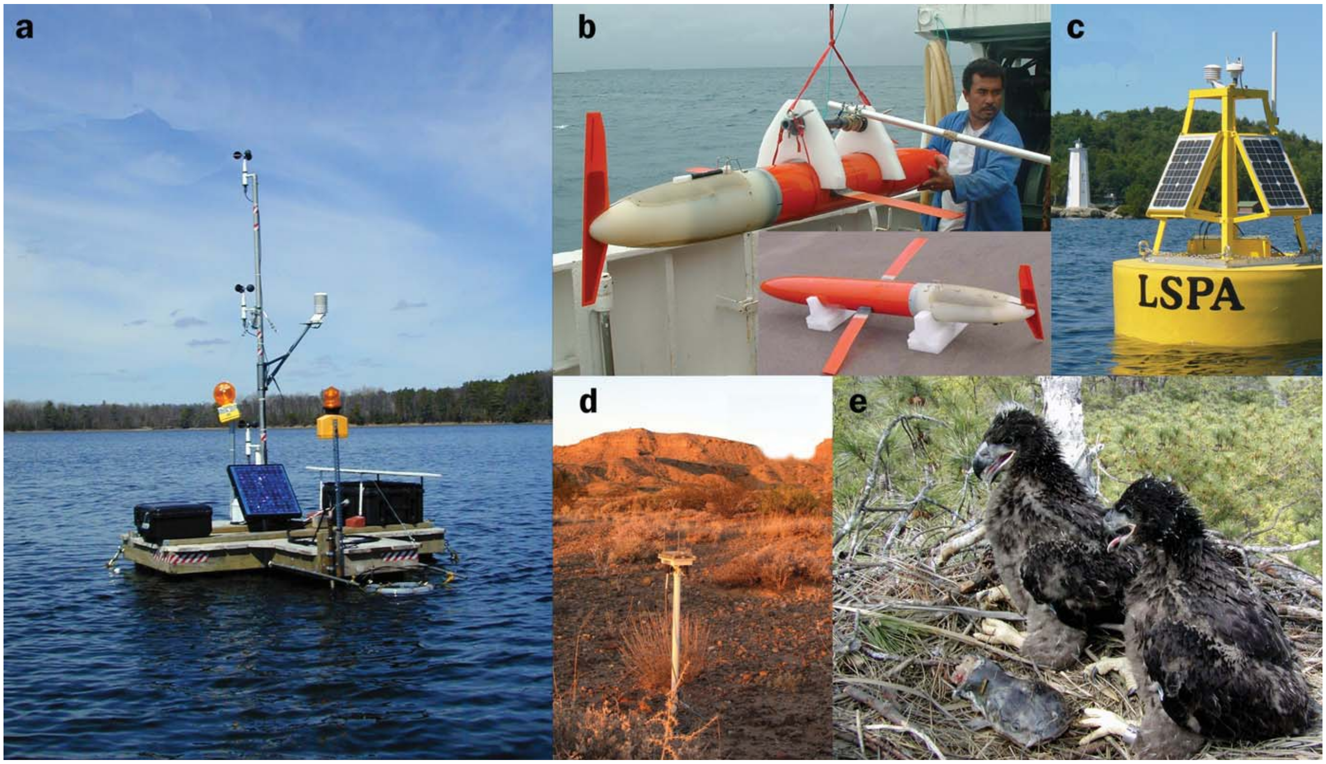

Figure 1. (a) Automated buoy on Sparkling Lake, Wisconsin; (b) Spray glider being deployed off the California coast at the start of its patrol of a 400-kilometer transect; (c) a Global Lake Observatory Network automated buoy on Sunapee Lake, New Hampshire; (d) a Sensor Web pod monitors ground and air temperatures at the Sevilleta National Wildlife Refuge in New Mexico; and (e) video-monitored bald eagle chicks feast on a blue catfish. Photographs: Timothy K. Kratz (a), Russ Davis (b), Marion G. Eliassen, courtesy of Kathleen Weathers (c), John H. Porter (d), and Bryan Watts (e).

In New York, long-term robotic measurements of limnological variables through the water column have led to insights on the recovery of Onondaga Lake from eutrophication (Effler et al. 2002, 2006, Denkenberger et al. 2006). Since 2002, robotic samplers in the lake, as well as a reference system (comparisons with Otisco Lake), have taken measurements and transmitted the data to researchers and to a publicly accessible Web page (*www.ourlake.org/html/onondaga_lake.html*). The long, detailed record of variation across multiple strata captured the physical, chemical, and biological characteristics relevant to eutrophication, and showed clear contrasts between Onondaga Lake's current state and its target state, as exemplified in Otisco Lake. The system continues to be used by researchers and the general public to track improvements in the condition of Onondaga Lake during a process of remediation.

In terrestrial systems, new understanding of desertification has emerged from measuring microclimate variability at broader spatial extents. Desertification—land degradation caused by the replacement of grassland by shrub-dominated vegetation—is occurring in arid lands worldwide. Shrub invasion increases the spatial heterogeneity of resources by creating "islands of fertility" scattered throughout areas of unvegetated soil. This heterogeneity in turn affects the distribution and abundance of associated species. At the Sevilleta LTER site in central New Mexico, a wireless network of Sensor Web pods (Delin 2002) was used to measure a suite of microclimate variables under different shrub species to determine whether all islands of fertility were equal (Collins et al. 2006). Researchers found that different shrub species have different effects on air and soil temperature or light availability, creating a more diverse set of microenvironments for associated species than was previously recognized. In addition, because the Sensor Web pods measured all variables simultaneously, new algorithms to detect sensor errors were developed to improve data quality. Thus, wireless sensor networks not only expand the spatial and temporal scales of measurement, but they also can provide new mechanisms to detect and correct measurement errors on the fly (Collins et al. 2006).

Estimating what cannot be observed

In studying ecosystems, we often care most about what cannot be observed directly. For example, the biological processes responsible for carbon transformations (ecosystem metabolism) cannot be directly observed *in situ* but can be inferred by their by-products. Photosynthesis rates can be estimated from observations of the state variables carbon dioxide (CO_2) or oxygen through time. It is common practice to develop ecosystem models that exploit the information

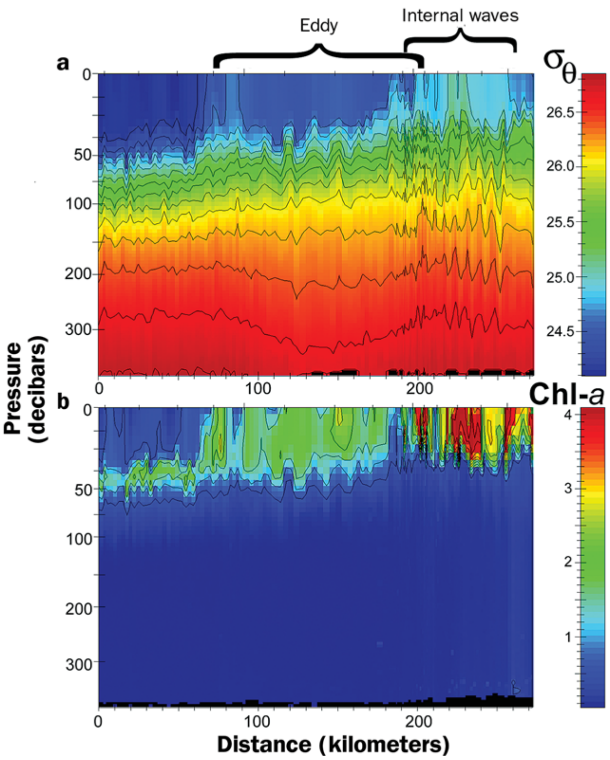

Figure 2. Vertical sections of (a) seawater density and (b) phytoplankton chlorophyll a *fluorescence from a Spray ocean glider patrolling along a transect off the California coast. The coast is to the right and open ocean to the left. The glider dived repeatedly from the sea surface to a depth of 400 meters (approximately 400 decibars pressure), measuring ocean properties on ascent. Depressions of density (σ_θ) surfaces below 100 meters indicate the presence of a mesoscale eddy. Internal waves in (a) are associated with increased phytoplankton chlorophyll-* a *standing stock in (b) (figure by Mark Ohman and Russ Davis).*

content of observable data to infer unobservable phenomena. Observations from any one sensor tend to show patterns at multiple timescales, and multiple sensors from a network of sensors can be used to integrate this scale-related information into an understandable whole. For example, researchers of the Global Lakes Ecological Observatory Network (GLEON) have deployed sensors to measure meteorological and limnological variables at high frequencies and to automatically transfer those data to repositories for analysis (Kratz et al. 2006). The goal of developing ecosystem models that exploit these data has drawn together a community of physical and ecological scientists and information-technology experts. An early product of the collaboration was a "now casting" model that describes the three-dimensional water circulation in a Wisconsin lake on the basis of the most recent observations of meteorological forcing conditions (Pan et al. 2006, Kimura 2007). This new understanding of the state of the lake's physics provides valuable information for studying fluxes related to biological processes. Sensor network measurements of dissolved oxygen and temperature profiles have demonstrated that different habitats in lakes differ in the rates of metabolism (i.e., primary productivity and respiration) (Lauster et al. 2006, Van de Bogert et al. 2007). Coupling lake circulation and metabolism models will help scientists understand how metabolism operates at the whole-ecosystem scale and will reveal, for example, the situations in which lakes are net sources or net sinks of atmospheric carbon. As researchers begin to assimilate data from multiple lakes in the GLEON network, they will broaden their estimates of lake metabolism to regional and ultimately global scales.

In a terrestrial setting, a worldwide network of micrometeorological towers (FLUXNET) makes high-frequency measurements of CO_2, water, and energy exchanges between terrestrial environments and the atmosphere to provide a basic understanding of carbon and water fluxes across ecosystems, including responses to disturbance (Misson et al. 2007). One of the primary components of ecosystem carbon exchange is soil respiration, the collective measure of respiration by soil microbes and plant roots with some contribution from soil fauna. Recent developments in both wireless (Johnston et al. 2004) and wired sensor technology (Tang et al. 2003) now allow for high-frequency measurements of soil respiration that can be coupled with other environmental parameters to calculate soil CO_2 fluxes in relation to key environmental drivers such as soil water content and temperature. Such high-frequency measurements can provide mechanistic detail to better understand carbon exchange between terrestrial systems and the atmosphere. At the Sevilleta LTER site, scientists have installed a sensor network that measures soil CO_2, moisture, and temperature at three depths in a monsoon rainfall manipulation experiment to determine soil CO_2 fluxes in response to highly variable summer precipitation (figure 3). Arid-land ecosystems are characterized by a pulse-reserve paradigm in which a rainfall event triggers biological processes that result in a measurable response, such as soil respiration (Reynolds et al. 2004, Collins et al. 2008). Thus, understanding system responses at the event scale will yield detailed information on soil respiration that can be used to interpret the main components of net ecosystem exchange as measured by a nearby flux tower. An analysis of flux tower data at the Sevilleta LTER site showed that even when soil water was available, a rainfall event during the summer monsoon led to a net CO_2 efflux despite active photosynthesis by plants (Kurc and Small 2004). These CO_2 pulses lasted only one to three days. The network of soil CO_2 sensors shows how soils "respire" at different depths, confirming that small rainfall events essentially stimulate microbial respiration in shallow soil layers (figure 4).

Unexpected results and new paradigms

Exposure to novel and diverse ecosystems led Charles Darwin to question the paradigms of his time, ultimately leading to the theory of evolution through natural selection (Darwin

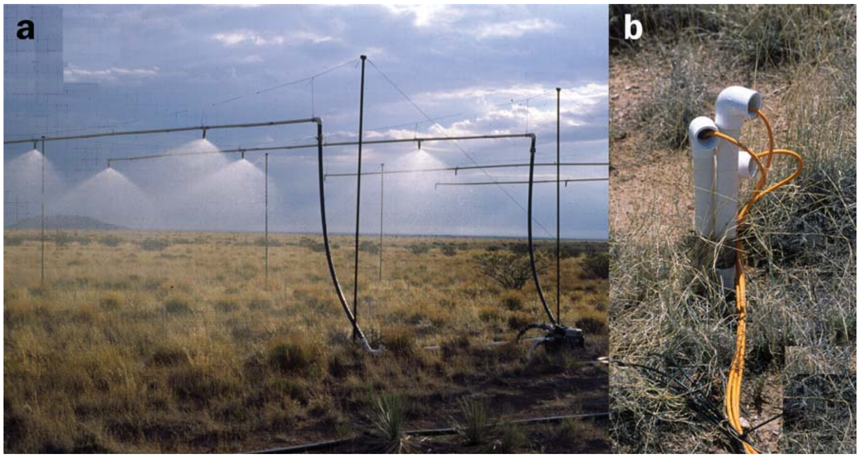

Figure 3. (a) Monsoon rainfall experiment in desert grassland at the Sevilleta Long Term Ecological Research Station in central New Mexico. (b) Sensor array for measuring soil water content, temperature and carbon dioxide at three depths (2, 8, and 16 centimeters).

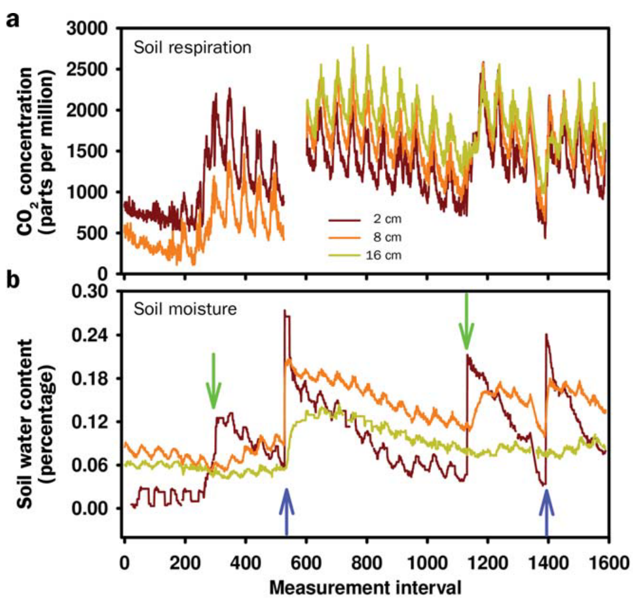

Figure 4. Changes in soil carbon dioxide (CO_2) content (a) and soil moisture (b) in response to natural (green arrows) and experimental 20-mm rain (blue arrows) events. There is a clear CO_2 concentration gradient from deeper to shallower soils as a function of root respiration. Rainfall events briefly reverse this gradient, primarily through microbial respiration at the soil surface.

1859). Novel data, such as those that led to the recognition that lakes lose carbon to both sediments and the atmosphere, also led to the discovery that terrestrial inputs were a major source of carbon in lakes (Hanson et al. 2003). Similarly, automated sensors that collect novel data, or even traditional data at novel scales, can enable analyses that inspire new paradigms or even subdisciplines in ecology. For example, typical studies of CO_2 dynamics focus on local processes, with an emphasis on vertical fluxes. However, a high-density meteorological sensor network at the Andrews Experimental Forest LTER site in Oregon revealed a "river of air" flowing along topographic gradients within the forest. Researchers subsequently discovered that a large mass of cold air flowing downward through the valley was taking with it high concentrations of CO_2. This changed the paradigm of how CO_2 is transferred between the forest and atmosphere from a diffuse, vertical flux to a concentrated horizontal flux. Flowing air is now sampled to assess basin-scale ecological processes, such as respiration (Pypker et al. 2007a, 2007b), in much the same way that watershed researchers use chemical measurements of water flowing out of a watershed to characterize ecological changes (Bormann and Likens 1979).

Sensors deployed for one purpose often turn out to serve another, sometimes with surprising results. During a survey of members of the Organization of Biological Field Stations (OBFS), we heard numerous stories of the unexpected utility of sensors. For example, sensors documented temperature, light, humidity, and wind conditions when a large forest fire swept through the Taylor Ranch Wilderness Research Station and traveled over an automated meteorological station (Holly Akenson, Taylor Ranch Field Station, Cascade, ID, personal communication, 21 September 2007); a wind profiling sensor at Kessler Farm Field Laboratory in Oklahoma made it possible to predict the locations of a huge F5 tornado as it moved through the Oklahoma City area, leading to warnings that very likely saved many lives (Linda L. Wallace, Kessler Farm Field Laboratory, University of Oklahoma, personal communication, 31 August 2007); tidal monitoring stations in South Carolina detected small (approximately 10 centimeters) tsunami waves from an undersea event near the Kuril Islands in Russia (Steve Rumrill, South Slough National Estuarine Research Reserve, Charleston, OR, personal communication, 20 September 2007); and a timed series of Webcam images, aimed at following leaf phenology, showed that the ends of tree branches moved up and down during the year by one to two meters in response to the weight of leaves (Mark Stromberg, Hastings Natural History Reservation, Carmel Valley, CA, personal communication, 7 September 2007).

The calls of birds, the babble of a brook, the rustle of a breeze through tree leaves, and the sound of a passing truck all have the potential to tell us something about the character of a place and time. Stuart Gage and his collaborators have deployed microphone-equipped sensor networks to collect sounds across landscapes, or "soundscapes," and have developed sophisticated computational tools for managing and analyzing the resulting torrent of data (Gage 2003, Krause and

Gage 2003, Butler et al. 2006, 2007). They have discovered relationships between the acoustic diversity of a soundscape and biological diversity, determined species arrival times to a habitat, created indices of disturbance by computing the ratio of technical and biological sounds, analyzed time series of sound in a habitat to assess diurnal and seasonal change, and developed libraries of species-specific signatures to enable automated census of vocal organisms. Advances continue to be made in the area of automated species identification (Yao Y. et al. 2006, Cai et al. 2007, Kasten et al. 2007, Trifa et al. 2008), with the added ability to triangulate sound and thus enable objective determination of breeding territories (Chen et al. 2003).

Current practice at biological field stations

We have seen some examples of how automated sensor systems have been used, but how widespread is that use in field biology and ecology? To examine current practices, we focused on biological field stations. Biological field stations have a long history of facilitating biological and technological discovery in North America. They are credited with incubating fundamental theory and recognized as critical training grounds for generations of field biologists. They also have played important roles in the development of technology. Important examples of scientific and technological advances emerging from work at field stations in the United States include the development of sonar and radar technology in World War II as part of research on bats in the 1930s at the E. N. Huyck Preserve and Biological Station (Galambos and Griffin 1941, 1942, Griffin 1944, 1946), perhaps the most important military application of new technology of the 20th century. The link between a deadly hantavirus epidemic in the Southwest in 1993, deer mouse populations, and El Niño was revealed by data from the Sevilleta field station (Yates et al. 2002). Similarly, research at Jasper Ridge Biological Preserve, the Sky Oaks Field Station, and other field stations identified the limited potential for future carbon storage in certain habitat types in North America early in the climate change debate (Hungate et al. 1997, Cardon et al. 2001, Hu et al. 2001, Shaw et al. 2002, Luo et al. 2007).

The OBFS is a consortium of more than 200 terrestrial-based field stations and marine laboratories distributed throughout North and Central America dedicated to supporting and facilitating modern field biology. Field stations host a wide array of research and educational activities involving university- and college-based research and courses; research projects funded by national, state, and local governmental agencies; and individual researchers. In 2007 we distributed an online survey to member stations of the OBFS to explore the state of development of advanced sensor systems at field stations and to get feedback on the opportunities and constraints that affect such development. Results of the survey are presented here (tables 1, 2, 3). (The survey text and a copy of the raw survey summary are available online at *http://wireless.vcrlter.virginia.edu/local/OBFS_2007_survey/Summary_Survey_Results.pdf.*)

The goals of the survey were twofold: (1) to assess current practice at field stations regarding the use of automated sensors, how sensors were being employed, the use of sensor networks, Internet connectivity, and data management systems, and to identify the contribution advanced sensors are making in the expansion of research at large spatial scales and higher-frequency temporal scales; and (2) to identify gaps in existing infrastructure that result in the inability to collect data at important spatial and temporal scales, and to identify ways to best fill those gaps to improve data collection scope and efficiency.

One hundred field stations participated in the survey, almost half the OBFS membership. We asked respondents to identify up to three specific sensor systems to report on in detail. The survey respondents provided information on 132 individual sensor systems. Use of automated sensors was widespread at the responding field stations, with more than 80% of stations deploying one or more automated systems (table 2). Sensor systems were focused predominantly on measurements of the atmosphere (54%) and water (30%). Systems focused on soil and organisms were rare, making up less than 14% in aggregate (figure 5a). However, when asked what measurements respondents would like to make, a different picture emerged, with only 35% of responses requesting additional sensors for atmospheric and water measurements (figure 5a). There was a clear desire for more ways of acquiring information about the behavior, physiology, and population levels of organisms (a 28% disparity between the desired systems and current systems) and characteristics of soils (a 12% disparity). Fortunately, there are some development efforts going on in these areas. For example, Allen and

Table 2. Summary results from a 2007 online survey of members of Organization of Biological Field Stations.

Survey question topic	Percentage of affirmative answers from 100 respondents
Use of automated sensors	81
Connectivity	
High-speed Internet	82
Wired links to sensors	42
Wireless links to sensors	42
Frequency 900 MHz	58
Frequency 2.4 GHz	35
Frequency 5.8 GHz	10
Frequency VHF	10
Manual downloads	82
Funding for sensor systems	
Government grants	67
Private or commercial	62
Internal or parent institution	55
Sensor systems implemented	
In the past five years	60
In the last year	18
Plans to upgrade sensor systems	
In the next 12 months	31
No plans to upgrade	14

Note: The survey was designed to assess current network and sensor-array infrastructure, spatial and temporal scope of advanced sensor systems, and technology and data-processing needs at field stations. Many questions allowed multiple responses (e.g., a given station might have both wired and wirelessly connected sensors), so percentages within a section will not sum to 100%.

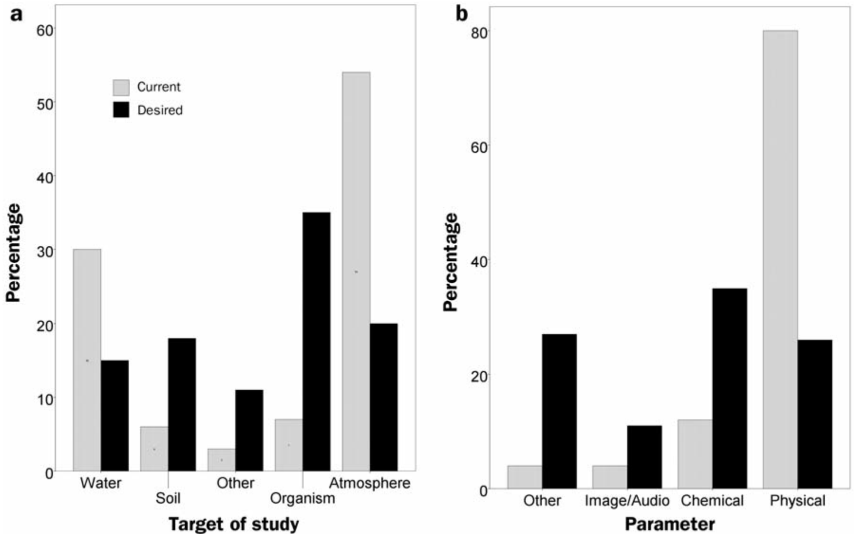

Figure 5. Percentage of sensor systems in the Organization of Biological Field Stations survey classified by (a) target of measurement and (b) type of parameter being measured. "Current" systems are those that are now deployed. "Desired" systems are those that do not yet exist but were listed by survey responders as systems they would like to deploy.

colleagues (2007) discussed an array of technologies for analysis of soil chemistry and root growth undergoing testing at the James Reserve (an OBFS field station in California).

When we examined the types of measurement being made, we saw a similar pattern. Currently deployed sensor systems are dominated by measurements of physical parameters, such as temperature or wind speed, and chemical and unconventional data such as images, sounds, and physiological measurements made up less than 20% in aggregate. However, when we asked respondents what types of parameters they would like to measure, chemical sensors came to the fore (figure 5b), along with the catchall "other" class, which included things like phenological measurements and DNA assessments. Unfortunately, although there have been some advances in the area of chemical sensors (particularly for homeland security), Johnson and colleagues (2007) reviewed *in situ* distributed chemical sensors for aquatic environments and concluded that most samples need to be returned to the laboratory for analysis, and that "the rate of progress in developing new sensors capable of long-term operation is not rapid enough to anticipate the time when a much broader suite of chemicals can be sensed autonomously" (p. 638).

Many sensor systems make extensive use of networking technologies. High-speed Internet access was nearly ubiquitous at the responding field stations (table 2). The vast majority (82%) of stations now have high-speed Internet service, with 42% having speeds of 1.5 megabits per second (T1) or higher. In contrast, an informal poll conducted at the OBFS annual meeting in 1999 indicated that only about 10% of stations had high-speed Internet connections. For the individual sensor systems, most data were transmitted through a serial or network connection (68%). However, 82% of the stations still used manual retrieval for at least one sensor system. For sensor systems that were connected, percentages for wired and wireless connections were identical at 42%. Wireless connections were dominated by wireless serial connections using the 900 megahertz radio band. The oldest wireless technology, using VHF (very high frequency) radios, was used at only 10% of the stations.

Porter and colleagues (2005) noted that wireless sensors provided unprecedented capabilities for data collection at high frequencies over broad spatial scales. As deployed at OBFS field stations, connected sensor systems dominated high-frequency measurements (figure 6a) but were not preferentially used for more spatially distributed systems (figure 6b). The sensor systems reported in the survey varied from one to more than 100 "nodes" (nodes are clusters of sensors that measure single or multiple parameters at the same location; for example, a meteorological station measures both temperature and rainfall at the same location and would be considered a single node). However, most sensor systems were relatively small, with a median of three nodes per system. Fewer than 10% of the sensor systems included more than 25 nodes (table 3). For each system, we also requested information on how important different elements were in deciding to implement an automated system. Respondents rated "improvement in data quality" and ability to make "high-frequency observations" higher than all other categories (table 3).

In summary, although automated sensor systems are widely used at biological field stations, they have not yet reached their

Table 3. Summary of 105 sensor systems reported in the survey by members of the Organization of Biological Field Stations.

Topic	Percentage
System size (number of nodes)	
Single node	37
Three or fewer	54
Twenty-five or fewer	91
Reasons for using (percentage who responded "important")	
Quality of data	61
High frequency	54
Cost of personnel	42
Real-time data	40
Cost of system	37
Unobtrusive observation	32
Ease of use	32
Remote control	28
Wide area	25

Note: Each station could include responses for up to three sensor systems.

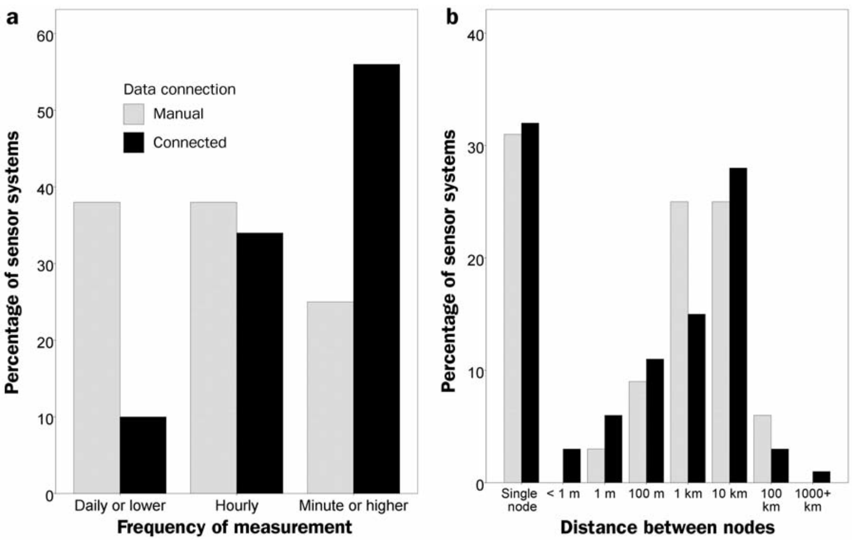

Figure 6. (a) Frequency of measurement for manually collected versus connected (a wired or wireless connection). Connected sensor systems typically collect data at a much higher frequency than do manually collected systems. (b) Distance between nodes for connected and manually retrieved sensor systems. There are no detectable differences in connectivity based on internode distance.

full potential, as reflected by the expressed desire for new types of sensors and by the relatively small number of nodes in each system. Respondents identified the lack of resources for development and operation as a primary challenge, followed by a need for improved information management infrastructure and for wireless networks. Sensor system installation and expansion within OBFS has been proceeding rapidly. Sixty percent of all sensor systems reported were deployed in the past five years, 18% of them in the past 12 months, and 31% of stations plan to upgrade sensor systems in the next 12 months. Interestingly, when we asked, "Have sensor networks already led to new ecological understanding?" 83% agreed, but fewer than half agreed strongly (47%). In contrast, when we asked, "Will sensor networks be increasingly important for advancing ecological science in the future?" more than 97% agreed, with 75% agreeing strongly.

Opportunities and challenges

Advanced sensor systems are helping us gain new insights in diverse ecological landscapes. The examples presented above are illustrative, but are not exhaustive. As the survey of biological field stations showed, sensor systems are being widely used by ecologists and new sensor systems continue to be developed at a rapid rate, with 18% of the field station sensor systems being deployed within the last year alone. We are beginning to see the connection between sensing (observing) systems and ecological theory (e.g., the "river of air" example) and analytical and predictive models (e.g. "now casting," netflux).

Development of individual sensors and local networks of sensors still presents challenges, foremost of which are providing new, robust field sensors and adequate power resources. Yet those challenges are being met as ecologists, computer scientists, and engineers collaborate on developing increasingly robust sensor systems that use field computation to optimize system performance to reduce power requirements (Vernon et al. 2003, Yao K. et al. 2003, Szewczyk et al. 2004, Arzberger et al. 2005). However, as indicated by our survey of field stations, the need for new types of sensors—particularly for chemical and organism-based measurements—continue to be unmet.

As we look forward, we anticipate more widespread adoption of sensor and sensor network technologies. We predict that the greatest potential for sensor systems to improve ecological understanding is at larger spatial scales where environmental pulses (e.g., typhoons) and presses (e.g., increased CO_2 in the atmosphere) interact to affect ecosystem services and responses. Whether this potential is realized depends on the development of sensor networks at broad spatial scales. Progress on such networks has been much slower than with individual sensor systems. Our survey of OBFS member stations found that existing sensor systems were much more focused on higher temporal resolution (higher frequencies of observation) than on broader spatial scales. Many of the examples presented here were single sensors or local networks focused on similar types of data. Development of such local networks (sensors, software, and people) is a precondition for network-level science. Other needs exist in addition to the development of the sensor system itself: even simple systems require a level of information technology expertise for system maintenance and troubleshooting, integration of analysis tools with database systems, and the development of appropriate interfaces to control data flows and extract data. Many local networks also collect diverse data types, such as soil nutrients, moisture, CO_2 concentrations, and temperature (as at Sevilleta, e.g.). Such diverse data are even more challenging to manage and integrate, often requiring development of specific models to interrelate sensor data. Individuals with the full set of required technical skills are rare in ecology. Thus, a key consideration in the use of the new technologies is training. Undervaluing this investment greatly increases the danger of failure.

Collection of similar types of data across broad geographical areas is currently the domain of research networks rather than individual researchers or research projects. GLEON is an example of a grassroots research network that is collecting similar kinds of data over very large spatial scales (Hanson 2007). Such networks take advantage of distributed sites to gather data to support comparative analyses on a particular phenomenon. Here, data standardization and controlled vocabularies facilitate data synthesis and comparison. At this scale, network governance (e.g., rules for sharing data, attribution) and the creation of a social framework for collaboration are important and largely unexplored social issues.

Many of the challenging questions in environmental science demand complex networks of sensors gathering diverse types of data. Data discovery (locating all of the relevant data) and data integration (using diverse data to address key environmental research questions) are major challenges. Large-scale environmental research and education networks are only in the beginning stages of development and implementation (e.g., National Ecological Observatory Network, Water and Environmental Research Systems Network, Ocean Observing Initiative, and American Distance Education Consortium). In this context, biological field stations have a key role to play in developing a data sharing and archiving network to enhance data collection, integration, and dissemination. Through these collaborations, sensor deployment and network development may progress most efficiently by integrating existing regional and global consortia.

In summary, the societal need for more rapid and sophisticated answers to questions at regional, continental, and global scales demands new scientific approaches. Sensor systems will play a necessary role in that effort, but sensor networks alone are not sufficient. We also need to improve mechanisms for the transfer of ideas among ecologists and between ecologists and information technology experts. Integration across these areas and other disciplines is often difficult for traditional, small research teams because few groups have all of the requisite expertise and resources. Furthermore, research at the regional or global scale will require networks of networks. This level of research requires the integration of scientific expertise, models, diverse approaches for capacity building, and information technology, which is typically scattered among disparate research programs in different fields. These challenges are common to all subdisciplines of ecology, and they must be overcome to build network-scale science. Nevertheless, as the use and functionality of sensor systems grow at networks of field stations and elsewhere, we will greatly improve our ability to gather high-resolution, large-scale data sets to answer fundamental questions about broad-based environmental change.

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