Biological Field Stations: Research Legacies and Sites for Serendipity

WILLIAM K. MICHENER, KEITH L. BILDSTEIN, ARTHUR McKEE, ROBERT R. PARMENTER, WILLIAM W. HARGROVE, DEEDRA McCLEARN, AND MARK STROMBERG

Biological field stations are distributed throughout North America, capturing much of the ecological variability present at the continental scale and encompassing many unique habitats. In addition to their role in supporting research and education, field stations offer legacies of data, specimens, and accumulated knowledge. Such legacies often provide the only framework for documenting and understanding the nature and pace of ecosystem, regional, and global changes in environmental conditions; ecological processes; and biodiversity. Because of these legacies and because they serve as gathering places for a rich diversity of highly creative and motivated scientists, students, and citizens, biological field stations are frequently where serendipitous scientific discoveries take place. The inclusion of biological field stations in environmental observatories and research networks ensures that these places will continue to foster future serendipitous scientific discoveries.

Keywords: biological field stations, long-term research, research legacies, serendipity, socially relevant research

Serendipity—the propensity for making surprising discoveries—is common throughout biology. Prominent examples include the discoveries of penicillin (Fleming 1929), meiosis (Beneden 1883), and cellular immunity (Metchnikoff 1901). It has been argued that major scientific discoveries cannot be premeditated, that they are instead the consequence of scientific preparedness of mind and, to a lesser degree, luck (Medawar 1984, Smyth 1990). The role of luck in scientific discovery is difficult to quantify. As Peter Medawar (1984) noted, "we know when we benefit from luck, but from the nature of things, we cannot assess how often bad luck deprives us of the chance of making what might have been an important discovery—the discoveries we did not make leave no trace" (p. 49).

Serendipitous discoveries in ecology have been associated with the origin of novel questions, examination of patterns and processes in unique environments or environments under extreme stress, employment of new technologies, sampling outside the scientists' normal disciplinary realm, and simply being in the right location at the right time. "Why is cannibalism rare?" is one example of a novel, or at least unusual, question that led to new discoveries, which culminated in documentation of the role of pathogen transmission as a selective force against cannibalism in salamanders (Pfennig et al. 1991). The role of a unique environment in serendipity is illustrated by discoveries of species and communities that live in extreme habitats, from deep-ocean hydrothermal vents (Enright et al. 1981) to mountain cliffs (Krajick 1999). The chance use of a new technology, the hydrophone, in studies of fish behavior led to development of the field of fish bioacoustics (Myrberg 1996). Likens (1989) and Magnuson (1990) provided numerous examples of the types of discoveries associated with sampling outside typical—that is, long-term—time frames for studies. A classic example of the importance of being in the right location at the right time is the observation of short-lived (5 to 15 minutes), precisely timed, species-specific mass spawning events by siphonous green algae on coral reefs (Clifton 1997). Furthermore, much of what we know about the effects of natural and anthropogenic disturbances is at least partially related to being in (or near) the right place at the right time.

BioScience 59: 300–310. ISSN 0006-3568, electronic ISSN 1525-3244. doi:10.1525/bio.2009.59.4.8

A propensity for making unexpected and fortunate discoveries is not entirely due to chance, as Norris (1995) asserted. In addition to the role that scientific preparedness of mind may play with respect to serendipitous discoveries, we assert that a biological field station as a place that comprises facilities, legacies of research, and nearby field sites plays a much more central role in scientific discovery than simply being a location where surprising discoveries are made. This may be especially true where the discoveries are particularly significant and have broad social relevance.

In this article we examine three major scientific accomplishments made at biological field stations: (1) documentation of the relationship of the decline and subsequent recovery of eastern populations of bald eagles (*Haliaeetus leucocephalus*) to the widespread use of organochlorine pesticides, based on monitoring studies at Hawk Mountain Sanctuary (the Acopian Center for Conservation Learning) near Kempton, Pennsylvania; (2) development of an understanding of and the capability to forecast the spread of *Sin Nombre hantavirus* and West Nile virus, based on research at the Sevilleta Research Field Station south of Albuquerque, New Mexico; and (3) creation of the theoretical framework for ecosystem management, based on field research and synthesis at the Andrews Experimental Forest east of Eugene, Oregon.

We identify many of the underlying factors that contributed to these three important scientific breakthroughs. We pay particular attention to the role that "place" played in these and other well-documented discoveries made at field stations across North America. Finally, we argue that field stations are places where preparedness of mind is fostered, enabling surprising discoveries of both scientific importance and social relevance. Field stations are vital to the national and global science enterprise and will continue to play a key role as standalone entities, as well as integral components of existing and emerging research networks and environmental observatories.

Scientific discoveries at biological field stations: Three case studies

Key discoveries with wide-ranging scientific, natural resource management, and societal implications have emerged from North American biological field stations. Serendipity played a role in each of the following three case studies, which also benefited from long-term observation and monitoring programs, field research and experimentation, and concerted synthesis efforts.

The demise and recovery of bald eagles. Much of what we know about the impact of organochlorine pesticides on populations of North American birds owes its origins to monitoring efforts initiated in the mid-1930s in response to an entirely different threat: direct persecution of raptors by those who considered the birds to be pests. Adult and juvenile bald eagles have been counted on autumn migration at Hawk Mountain Sanctuary, the world's first refuge for birds of prey, since 1934 (figure 1). A combination of northeast to southwest Appalachian Mountain topography and prevailing northwesterly winds position the sanctuary along a major migration corridor for soaring migrants, including 16 of North America's 33 species of falconiforms. The counts, which have been conducted in all years since 1934, excepting the war years 1943–1945, represent the longest and most complete

*Figure 1. Immature bald eagle (*Haliaeetus leucocephalus*; near) and sharp-shinned hawk (*Accipiter striatus*; distant) (top) viewed from the North Lookout at Hawk Mountain Sanctuary, Pennsylvania (bottom). Photographs: Shawn P. Carey.*

record of raptor migration in the world (Broun 1949, Bildstein 1998, 2006).

The sanctuary, which was established to stop the shooting of thousands of hawks, eagles, and falcons migrating past the site each autumn, initiated the counts primarily to document the size of the flight and the success of its conservation effort (Broun 1935). It soon became apparent, however, that a series of annual migration counts would allow the sanctuary to track fluctuations in regional raptor populations, and by the second year of operation, migration counts became the primary objective of sanctuary fieldwork (Broun 1939, 1949). Initially, counts were made almost entirely by the sanctuary staff. By the early 1950s, however, volunteer hawk-watchers were conducting 24% of the counts; and during the first half of the 1990s, they were conducting 37% of the counts. Before 1996, counts consisted of daily totals of raptors, together with an indication of count effort in hours. Since 1996, counts have been recorded hourly (Bildstein 1998).

Bald eagles have been part of the database since an adult eagle was recorded on 30 September 1934, the first official count day. A unique bimodal distribution in the seasonal timing of bald eagle passage at the site, with a principal movement peaking in late August to early September, and a smaller, secondary movement peaking in mid-November, suggests that both northern and southern populations of bald eagles migrate past the sanctuary, and that most of the birds counted at the site represent southern individuals, most of which nest in Florida (Broley 1947, Bildstein 1998).

By the mid-1950s, annual ratios of juvenile to adult bald eagles sighted at Hawk Mountain were less than half of what they had been in the 1930s (figure 2). Less than a decade later, Rachel Carson used the sanctuary's then 25-year record of eagle numbers as part of her argument against the widespread use of organochlorine pesticides in North America (Carson 1962). What is particularly remarkable about this case is that the same long-term database, the collection of which continues today, tracked not only declines in ratios of juveniles to adult bald eagles but also a predictably lagging decline in the total numbers of eagles counted at the site, as well as subsequent rebounds in both measures of population status following bans on the widespread use of DDT (dichlorodiphenyltrichloroethane) in North America in 1972 (figure 2; Bildstein 1998, 2006).

Even more remarkable is the fact that another unrelated example of serendipity helped precipitate our understanding of the mechanism by which DDT affected bald eagle reproductive success. British ecologist Derek Ratcliffe used eggshells collected for private and public museums earlier in the 20th century to help document pesticide-era reductions in eggshell thickness in peregrine falcons (*Falco peregrinus*) and other predatory birds (Ratcliffe 1967). Ratcliffe's work was a critical first step in understanding the physiological mechanism by which DDT and other organochlorine pesticides were affecting birds of prey (Cade et al. 1988).

Understanding the emergence and spread of hantavirus and West Nile virus. Initial discoveries of emerging pathogens are frequently made by public health workers and wildlife specialists from a variety of state and federal agencies, but established field stations provide the infrastructure, staff, and staying power to develop the specific knowledge necessary to understand the life cycle and ecology of local invasive or emerging disease vectors and pathogens once they have been identified. An example of such a serendipitous event took place in the spring of 1993, when a new deadly disease emerged in the Four Corners region of the American Southwest. The pathogen was unknown to medical science, had no known cure or effective treatment, and inflicted a 70% mortality rate during the first few weeks of the outbreak. Victims initially developed flulike symptoms, then progressed quickly to a respiratory crisis stage as the lungs filled with fluids; death often followed within hours. Scientists from the Federal Centers for Disease Control and Prevention responded immediately and quickly identified the pathogen as a new strain of hantavirus (*Sin Nombre hantavirus*; Nichol et al. 1993); a short time later, additional research identified the deer mouse (*Peromyscus maniculatus*) as the pathogen's host (Childs et al. 1994). The disease, hantavirus pulmonary syndrome, was

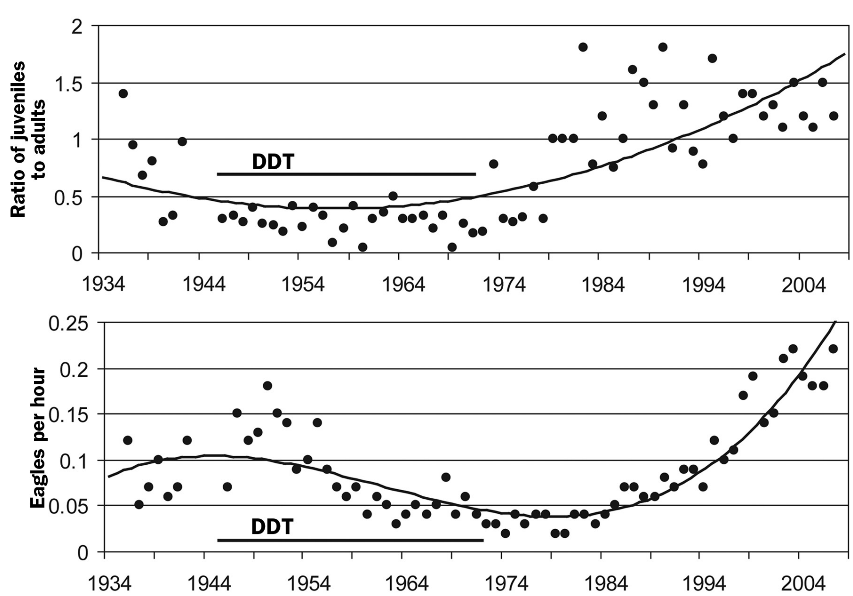


Figure 2. Ratios of juvenile to adult bald eagles (top) and total bald eagles per hour (bottom) counted at Hawk Mountain Sanctuary, Pennsylvania, from 1936 to 2007 (excluding the war years 1943–1945 when counts were not made; data from 1934–1935 have been omitted because records of juvenile counts were incomplete).

found to be transmitted to humans through aerosolized rodent feces and urine carrying live virus particles, and was typically acquired by people cleaning rural homes and outbuildings infested with deer mice.

However, many questions remained: Was this a newly evolved virus, or one that had existed undetected for many millennia? Or was the outbreak the result of a deliberate act of bioterrorism? Some speculated that a military experiment may have gone awry (Horgan 1993). If it were a completely natural phenomenon, why did the outbreak occur when and where it did? What factors might regulate future outbreaks?

Five years earlier, ecologists with the University of New Mexico's Sevilleta Long Term Ecological Research (LTER) program and the Museum of Southwestern Biology had begun a series of long-term studies of rodent populations in grasslands, shrublands, and woodlands surrounding the Sevilleta Research Field Station on the Sevilleta National Wildlife Refuge (NWR) in central New Mexico. The original intent of the project was to evaluate the role of rodents as ecosystem keystone species, regulating the composition, abundance, and distribution of plant assemblages in the Southwest (e.g., Brown and Heske 1990) under the influence of highly variable climate drivers. By the spring of 1993, the accumulated data showed an association between increased precipitation in the 1991–1993 period (resulting from the concomitant El Niño Southern Oscillation [ENSO] period) and greater ecosystem productivity, accompanied by a lagged 3- to 20-fold increase in rodent densities (Parmenter et al. 1993). Higher rodent host densities would lead to greater rodent-human contacts, thereby potentially increasing disease transmission risk from rodent hosts to humans.

The Sevilleta LTER results were then compared with long-term climate and rodent density data from scientists with the National Park Service's Canyonlands National Park, Utah, located just north of the hantavirus outbreak region. Canyonlands is situated in southern Utah, a sparsely populated area that is expected to have encounter rates similar to those in the Four Corners region. Canyonlands was outside the region influenced by the 1992–1993 El Niño, and received only average precipitation during this time—and the local deer mouse populations had not increased. Importantly, southern Utah had not sustained any human hantavirus cases.

When precipitation data for the Four Corners outbreak region were examined, it was clear that the 1991–1993 El Niños had produced exceptionally high winter and spring precipitation. Extending the results from the Sevilleta study, it was very likely that rodent populations in the outbreak region had increased there as they had in central New Mexico (Parmenter et al. 1993). These data provided the explanation for questions concerning the epidemic's timing and location. In addition, analyses of deer mouse tissues archived in the Museum of Southwestern Biology's Genomic Resources Division showed that some individual mice collected nearly 20 years earlier were positive for *Sin Nombre hantavirus*; hence, the virus had clearly existed in the region for many years. Further genetic analyses uncovered a long evolutionary history between hantaviruses and North American murid rodents, going back at least 20 million years (Yates et al. 2002). Subsequent long-term research on rodent-pathogen interactions (figure 3) has led to a detailed understanding of the evolution and ecology of the rodent-virus dynamic (Yates et al. 2002) and corroborated the ENSO influence on human disease outbreaks (Hjelle and Glass 2002).

With a greater detailed understanding of the hantavirus-rodent-environment interaction, predictive spatiotemporal models of disease risk using satellite imagery have been developed (Glass et al. 2002, 2006). In 2005, researchers examined Landsat Thematic Mapper imagery of northern New Mexico and northeastern Arizona, and using algorithms developed during the 1990s identified areas of increased risk for hantavirus disease in the coming spring-summer period of 2006 (figure 4). The research team, led by Greg Glass, of Johns Hopkins University, publicized this forecast during the winter of 2005–2006 in an effort to alert public health officials (Glass et al. 2006). The expected number of human cases of hantavirus pulmonary syndrome in this region in an average year (e.g., 2005) was four cases, and in 2006 the number reached nine human cases, more than twice the normal number. These results demonstrated the utility of the predictive model, but also illustrated the difficulty in educating the public about an impending disease threat.

Another serendipitous opportunity arose when West Nile virus (WNV) emerged in New York and began spreading across the United States in 1999 (Nash et al. 2002), affecting humans, bird populations, and wildlife. Ecologists with the Sevilleta Research Field Station and the Albuquerque Environmental Health Department organized a detection

Figure 3. Biologists from the University of New Mexico collect blood samples from marked, live-trapped rodents to test for hantavirus infections. Rodents are then released to monitor long-term patterns of population densities, demographics, and infection dynamics.

and surveillance network of sites along approximately 750 kilometers of the Rio Grande in New Mexico from western Texas to southern Colorado. The objective was to identify the pattern and rate of WNV spread throughout the Rio Grande valley, identify the local mosquito species vector, develop efficient sentinel sampling methods, and characterize habitat types that would support chronic WNV infections. In 2003, the westward invasion of WNV entered the Rio Grande valley, appearing in New Mexico, Texas, and Colorado during the summer. The sentinel network of study sites succeeded in identifying the geographical patterns and vector species—*Culex tarsalis* (Coquillett) in rural areas, and *Culex salinarius* (Coquillett) and *Culex quinquefasciatus* (Say) in urban areas (DiMenna et al. 2006a), as well as revealing the most efficient monitoring methods and important habitats (DiMenna et al. 2006b). The fortuitous combination of the availability of local field-station infrastructure in a central location and collaborating, experienced personnel who had mobilized eight years earlier for the hantavirus research was paramount to the success of the WNV study. Both studies illustrate the value of field stations in developing detailed understanding of the ecology of emerging infectious diseases.

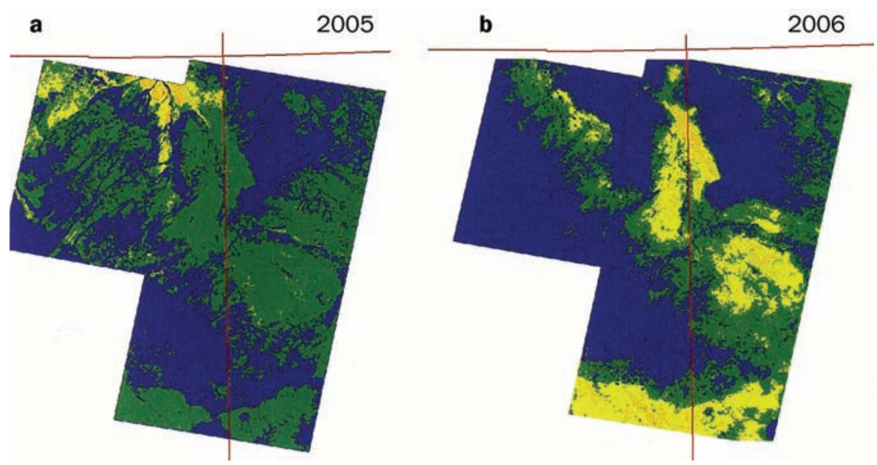


Figure 4. Forecast risk maps for hantavirus pulmonary syndrome (HPS) in 2005 and 2006 based on algorithms from satellite imagery (Landsat Thematic Mapper) taken in 2004 and 2005. Target area includes northwestern New Mexico and northeastern Arizona (shown in the top center of both images is the Four Corners area of Utah, Colorado, New Mexico, and Arizona). Warm colors (orange and yellow) indicate areas of higher risk, cool colors (green and blue) indicate low risk. Human cases of HPS in this area increased from four in 2005 to nine in 2006. From Glass and colleagues (2006).

Development of the Northwest Forest Plan and emergence of ecosystem management as national policy. The H. J. Andrews Experimental Forest, established in 1948, lies on the western slope of the Oregon Cascades east of Eugene. Specifically selected because of the old-growth Douglas-fir forests that cloaked the steep mountainous landscape, it was dedicated to research and education that would improve forest management. Research in the 1950s centered on logging methods and rapid forest regeneration. In the 1960s, research shifted to the effects of logging on water yield, sediment production, and nutrient cycling. The overall program expanded greatly during the International Biological Program of the 1970s, and many basic ecological studies examined how forest and stream ecosystems function (e.g., nutrient cycling, energy flow, community organization) in both old-growth and young managed forests. These basic ecological studies further expanded through the 1980s to include riparian research that focused on terrestrial-aquatic linkages, and evolved in the 1990s to landscape-scale studies of the interactions of patch patterns and network connectivity on maintenance of long-term productivity, including species diversity, and testing of ecosystem management concepts (McKee 1998).

During the 1980s, long-standing tensions between environmental organizations and the timber industry in the Pacific Northwest over logging of old-growth forests escalated into open battles carried out in the federal courts. On 23 May 1991, US District Court Judge William L. Dwyer enjoined logging on all federal lands throughout the range of the northern spotted owl until the US Department of Agriculture developed more defensible standards and guidelines for management of old-growth forest habitats.

Because of that injunction, the US Forest Service and the Bureau of Land Management needed credible scientific backing to explore alternatives and propose new management practices. The Andrews Forest was one of the few places with a legacy of research comparing the structure and function of old-growth forests and associated streams with young stands under intensive forest management. The Andrews Forest–based synthesis efforts on old-growth forest structure and function (Franklin et al. 1981), the importance of diversity (Franklin et al. 1989), and the ecosystem structure of streams and associated riparian zones (Gregory et al. 1991) contributed to the scientific foundation for a massive revision of forest management in the Pacific Northwest that culminated in the Northwest Forest Plan (USFS 1994).

Throughout the 1980s and early 1990s, the Andrews Forest scientists had been working with forest managers to develop the science framework from which emerged the basic principles underlying ecosystem management and demonstrations of approaches that employed those basic principles to forest management (figure 5). Key ecosystem management components included identifying information needs across multiple scales and species, assessing the role of historical disturbance patterns, using large scales (landscape to regional) for analysis, seeking consensus on desired future conditions, employing monitoring and evaluation, and using

*Figure 5. Clockwise from the upper left: (a) northern spotted owl, a species adapted to large unbroken blocks of old-growth conifer forest and an environmental symbol during the timber wars of the Pacific Northwest; (b) a tumbling stream in the Oregon Cascades with intact old-growth forest in the riparian zone; (c) an aerial oblique of a drainage in the Oregon Cascades with staggered clearcut areas that fragment the forest and reduce the connectivity of the landscape; (d) a public outreach presentation in an old-growth forest, where the multiple goals of ecosystem management are being discussed; and (e) a broadcast burn of a clearcut area to reduce the logging slash and shrubs that provide early-succession competition for planted seedlings but also reduce the overall biological diversity and ecosystem functional diversity of the site. Photographs: Al Levno (a, b, and c), Aaron McKee (d), and Art McKee (e), from the US Forest Service PNW-OSU Forest Science Data Bank image and photo library (*www.fsl.orst.edu/lter/data/cd_pics/cd_lists.cfm?topnav=116*).*

adaptive management (Thomas 1996). These science-based concepts and principles found a ready audience during the tumultuous regional planning effort triggered by the timber wars, and prepublication copies of papers discussing aspects of ecosystem management, such as the one by Cissel and colleagues (1994), were widely circulated. In 1992 ecosystem management became official US Forest Service policy and remains so today.

Interplay of place and serendipity

Place and other factors—many unforeseen—led to and amplified the scientific importance and social relevance of the discoveries and scientific syntheses described above. The ongoing raptor migration study at Hawk Mountain Sanctuary exemplifies how serendipity affected the rate at which ecology advances. First, purchase of a mountaintop refuge for raptors along a major migration corridor in 1934 (Broun 1949) set the stage for monitoring these secretive and wide-ranging birds whose populations are otherwise difficult to survey (Fuller and Mosher 1981). Second, the coincidental appearance of two new ornithological tools, binoculars and modern field guides (Peterson 1934), enabled conservationists to accurately count the migrants. Third, the development of hawk watching as outdoor recreation helped sustain the initial count, as well as ensure its continued simplicity, standardization, and proper record keeping. Fourth, eggshells collected for display and taxonomy purposes earlier in the 20th century enabled their use as historical benchmarks for later research on environmental contaminants. The long-term value of any one of these four events to ecology—let alone all of them—could not have been anticipated at the time.

Similar serendipitous circumstances apply to the emergent disease scenario played out in the Sevilleta NWR of New Mexico. The long-term rodent studies had been established several years earlier for a totally different purpose, yet they provided salient data for addressing the ecology of the hantavirus pathogen. Archived specimens and frozen tissues in the Museum of Southwestern Biology also were collected for other purposes (chiefly evolutionary, biodiversity, and parasite studies), but these specimens could be analyzed for viral infections years after they had been collected. Finally, the purely unexpected history of the Sevilleta NWR—its strategic location in the middle Rio Grande valley, its donation by the Campbell family to the US Fish and Wildlife Service explicitly for environmental research long before the recognition of global climate change, ENSO phenomena, and zoonotic disease ecology, and its eventual selection as an LTER site with attendant field station facilities—provided the stage against which all these disease ecology events would occur.

The Northwest Forest Plan and the underlying ecosystem management framework was a revolutionary change from the single-species or individual-project focus of past natural resource management by federal agencies. The legacy of databases emerging from evolving long-term studies at Andrews Forest provided a knowledge base that encompasses forest and stream ecosystem function in old-growth forest and young managed stands, the importance of biodiversity to forest ecosystem health, and the complex interplay of terrestrial and aquatic elements in Pacific Northwest landscapes. The existence of these databases and the emergence of new knowledge, coupled with the 1991 federal court injunction, opened a policy window (*sensu* Haeuber and Michener 1998) whereby a fortuitous combination of problems, scientifically based policy alternatives, and political streams converged, culminating in the Northwest Forest Plan. The high profile of the regional issues led to a concurrent national discussion of the scientific legitimacy of the principles of ecosystem management and their eventual adoption as national policy.

The case studies presented above provide tangible linkages between place and serendipitous scientific discovery. There are, however, less tangible aspects of field stations as special places that enable such discoveries. In particular, field stations evolve into small villages where resident scientists and students interact far more among themselves and with nonscientists than they might normally do on a typical university campus. The remote locale and sharing of housing, dining, and labs, as well as a tradition of openly discussing work under way on the lands around the field station, mean that scientists are often interacting directly with new people from diverse backgrounds and thus are able to make new connections and cross discipline boundaries. Examples of other socially significant research efforts at field stations that have benefited from the interplay of serendipity and place include the following:

- Working among a diverse group of hydrologists, geomorphologists, and river-rafting experts at the Angelo North Coast Reserve, Kupferberg and others (Kupferberg 1996, Kupferberg et al. 2008) found that water releases in July from dams on the Feather River to enable whitewater rafting were wiping out egg masses and tadpoles of the foothill yellow-legged frog. Their work led to extensive changes in release schedules from federal dam projects to enhance aquatic biodiversity.

- Bill Cade, a student at the Brackenridge Field Station in Texas, discovered that native crickets were parasitized by a fly that was able to home in on cricket sounds (Cade 1975). A fortuitous association with a mechanical engineer interested in this fly's ear led to a novel design for microminiature directional microphones (Yoo et al. 2002). Such microphones based on cutting-edge nanofabrication techniques are the basis for the next generation of human hearing aids.

- Simulating masting events in oaks with nearly four tons of acorns provided by local Girl Scouts at the Institute of Ecosystem Studies in New York, Jones and colleagues (1998) demonstrated that bumper crops of acorns in a given year, which are often documented only at field stations, can serve as a warning for a greater Lyme disease risk. Increased rodent populations allow greater survival of nymphal ticks, which translates into more Lyme disease in the environment and, subsequently, more human cases.

- Using stream insects to detect mining pollution near the Rocky Mountain Biological Station, Theo Colburn found dramatic endocrine-disrupting effects from what had previously been considered to be harmlessly low concentrations of a variety of chemicals. Colburn and colleagues (1993, 1996) have extended these observations that were initially made in relatively pristine mountain streams to show significant threats to human fertility from our water supplies.

North America's biological field stations: Past, present, and future

Biological field stations serve as gathering places for scientists to make discoveries about our natural environment. From molecular-level to global-change studies, field stations provide logistical and laboratory facilities; a secure place for deploying expensive instrumentation; and, moreover, a place for long-term repeated observations of vegetation, animal populations, soils, and climate. The wealth of data, physical and biological specimens, and publications represent rich legacies from studies performed over decades at biological field stations. As these legacies accumulate, knowledge of place grows and the opportunities for serendipitous discoveries concomitantly increase, as the case studies above illustrate.

Although the emphasis in this article has been on temperate North American field stations, ecologists are increasingly aware of the critical importance of tropical field stations everywhere (Whitesell et al. 2002, Bawa et al. 2004). The propitious circumstances for preparedness of mind and serendipitous discovery also occur at tropical field stations—facilities and logistical support, a thriving intellectual community, and long-term data sets. Furthermore, the tropical portion of the equation is clearly critical for an understanding of global problems such as climate change (Clark 2004), amphibian declines (Whitfield et al. 2007), and land-use changes (Sánchez-

Azofeifa et al. 2003). One prominent tropical field station is the OTS (Organization for Tropical Studies) La Selva Biological Station in Costa Rica. This station hosts approximately 300 scientists and 100 university courses every year. Over its 40-year history, the protected land area has tripled, but the more striking increases have been in station use, infrastructure, and publications (see box 1). Ease of access to the station has also dramatically increased so that an eight-hour car trip from the airport 20 years ago has now been reduced to two hours.

An important concern at many field stations is the ongoing land-use changes of properties contiguous to the field station and the associated loss of natural ecosystems. Additional land acquisition or protection through conservation easements is a central component of the stewardship practiced at many field stations, as shown in box 1. Public and private land trusts, private philanthropists, and conservation organizations are often directly involved in adding to field station holdings.

More than 280 field stations are located throughout North America. In some cases, as with the University of California Natural Reserve System, sites of new field stations have been selected to represent the span of environments within the state. More typically, though, field stations were acquired opportunistically through the efforts of biology faculty at small colleges, museums, and universities to facilitate research and teaching in ecosystems representative of the region. In addition to academic institutions, field stations are affiliated with both governmental and nongovernmental organizations. North American field stations vary in size from a few acres (with access to national parks or other public lands) to more than 220,000 acres (e.g., the Sevilleta Research Field Station located on the US Fish and Wildlife Service's Sevilleta NWR).

Interest in improving our understanding of and our capacity to forecast global environmental change at local to continental scales has led to the proposed creation of an international ecological network of networks (Peters et al. 2008). Such an umbrella network would comprise long-term ecological research sites, environmental observatory sites, field stations, and other networks of sites.

Field stations range in location from the University of Idaho's Taylor Ranch Field Station, centered in the largest block of wilderness in the conterminous United States, to the Fortuna Mountain Research Reserve, located in the metropolitan area of San Diego. For this article, we examined how well the 286 North American field stations associated with the Organization of Biological Field Stations (OBFS) represent global ecoregions (figure 6). Interestingly, the analysis demonstrated that the network of field stations—despite being concentrated in the eastern United States—provide good continental representation of worldwide ecological variability, especially in temperate and subtropical biomes. Most ecoregions in the eastern United States are well represented by OBFS field stations, as

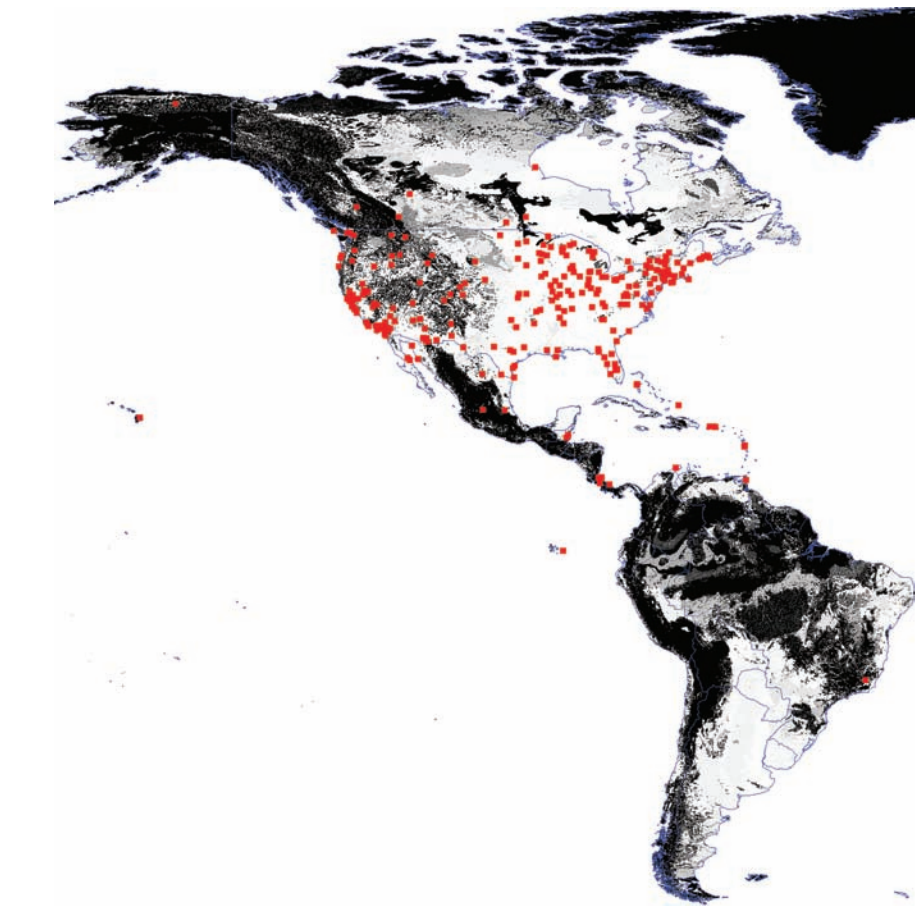
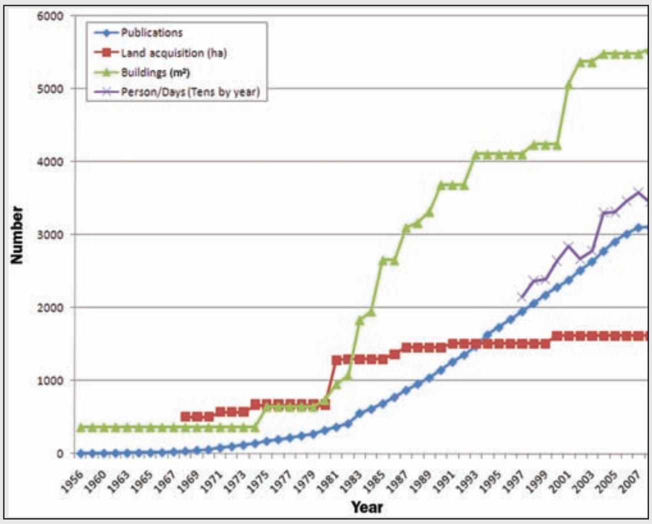
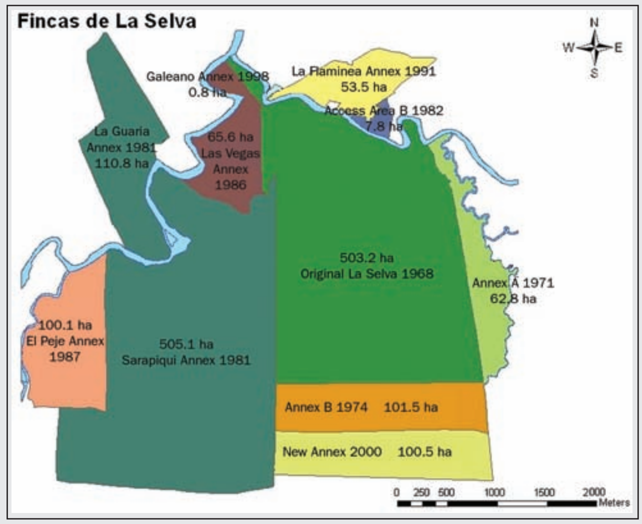


Figure 6. Representativeness of 286 members of the Organization of Biological Field Stations (OBFS), based on quantitative ecoregions. Five thousand quantitative global ecoregions were produced using multivariate clustering based on 14 climatic, soil, and physiographic conditions (elevation, compound topographic index, solar flux, potential plant available water capacity, soil bulk density, total soil carbon, total soil nitrogen, biotemperature, diurnal temperature range, moisture stress, precipitation in the driest quarter, precipitation in the wettest quarter, temperature in the coolest quarter, and temperature in the warmest quarter), as described in Hargrove and Hoffman (2004). By calculating the multivariate similarity between each quantitative ecoregion and the most similar field station, we quantified the degree of representativeness coverage for the network of OBFS sites (sensu ***Hargrove et al. 2003). The degree of multivariate similarity is coded to a gray level, with darker areas in the map indicating areas that are poorly represented by existing OBFS members; field stations typically are situated within well-represented ecoregions, which are colored white.***

Box 1. Growth of La Selva Biological Station.

The graph on the left presents a historical view of La Selva Biological Station in terms of land acquisition (red), scientific publications (blue), amount of infrastructure (green), and station use in visitor days (purple), by year, since 1997. The map on the right illustrates land acquisition over time. The values of the points for publications, land, and infrastructure represent cumulative figures. Station use is not cumulative but is a more or less annually increasing value of person-days of station visitation by user groups, including researchers, course and workshop participants, research project workers, natural history visitors, and others. La Selva Biological Station officially became part of Organization for Tropical Studies in 1968 but had been a site of scientific activity when it was still Leslie Holdridge's *finca* (farm); hence, the publications started before 1968. The apparent leveling off of the publication curve is an artifact of the lag time between publication of papers and their appearance in our bibliographic database.





are many locations in the western United States. OBFS ecoregion representation extends well beyond the conterminous United States and includes parts of Canada, such as Quebec, Ontario, and Manitoba; parts of Mexico, including Baja, Sonora, Chihuahua, Coahuila, New Leon, Tamaulipas, Veracruz, the Yucatan; the Caribbean; and the lowland portions of southern South America, including Argentina, Paraguay, and Uruguay. Because of their locations and the existence of infrastructure and long scientific legacies, OBFS field stations not surprisingly belong to and frequently dominate the membership of existing (e.g., LTER) and developing (e.g., National Ecological Observatory Network) environmental research networks.

Conclusions

Serendipity is inevitable in science. Although field biologists, ecologists, and environmental scientists have little or no control over chance and luck, they clearly can benefit by being in the right place at the right time. Moreover, scientific evidence at regional and broader scales will be anecdotal, circumstantial, and accidental as often as it is experimental (Hargrove and Pickering 1992). Surprising discoveries, however, are not predicated solely on luck. The case studies presented here illustrate that scientists increase their chances of making serendipitous discoveries by implementing simple, well-designed projects that extend beyond conventional scales of observation. In all instances, adequately documented and accessible long-term data provided the underpinning for surprising discoveries. For instance, simplicity and data standardization were key to developing the ongoing raptor database at Hawk Mountain. Despite some changes (e.g., a shift to recording counts hourly instead of daily), the raptor database contains a relatively small number of parameters that can be readily observed, quickly recorded, and easily taught to observers (Bildstein 1998, 2006). Such simplicity is especially important when data are to be collected in perpetuity by volunteers, whose membership changes considerably over time.

Many major scientific and socially relevant discoveries in the biological and environmental sciences have arisen from a fortuitous combination of events that were associated with biological field stations. Documentation of the precipitous decline of bald eagle populations at Hawk Mountain Sanctuary set the stage for Rachel Carson's translation of the science to society in *Silent Spring,* which summarized the salient science and told a story that captured the attention of the masses and eventually led to policy change.

Long-term data and knowledge, often accumulated by scientists and students over decades at field stations, may be the only basis on which we can document and understand the nature and pace of ecosystem, regional, and global changes in environmental conditions and in the earth's biota. Interestingly, the enormous value of the data and specimens held at field stations may not become fully apparent until an event occurs such as the hantavirus outbreak in New Mexico or the 1991 federal court injunction in the Pacific Northwest.

Incomplete knowledge, environmental stochasticity, and global and regional changes ensure that surprise will always be inevitable in ecological and environmental research. Biological field stations are far more than just places where research is performed or students are trained; they encompass unique habitats and physical and human infrastructure, as well as legacies of data, specimens, and accumulated knowledge. Field stations provide access to systems that cannot be replicated in the laboratory, organisms that cannot be domesticated, and complex ecological interactions that occur only in natural settings. Continued support for field stations through universities, federal agencies, nongovernmental organizations, and philanthropic individuals and organizations, as well as the inclusion of field stations in existing and emerging environmental observatories and research networks, ensure that biological field stations will be well poised to play an increasingly important role in future serendipitous scientific discoveries.

Acknowledgments

We gratefully acknowledge the support of the National Science Foundation (NSF) and the many program officers, including James T. Callahan and Gerald R. Selzer (both deceased), who enthusiastically and tirelessly guided the NSF Field Station and Marine Lab Program and otherwise contributed to the nationally important legacies represented in field stations and marine labs. The authors thank Barbara Kimbell and three anonymous reviewers who offered numerous suggestions for improvement. This is Hawk Mountain Sanctuary contribution to conservation science number 168.

References cited

Bawa KS, Kress WJ, Nadkarni NM. 2004. Beyond paradise—meeting the challenges in tropical biology in the 21st century. Biotropica 36: 276–284.

Beneden VE. 1883. Recherches sur la maturation de l'oeuf et la fecundation. Archives de Biologie 4: 265–640.

Bildstein KL. 1998. Long-term counts of migrating raptors: A role for volunteers in wildlife research. Journal of Wildlife Management 63: 435–445.

———. 2006. Migrating Raptors of the World: Their Ecology and Conservation. Ithaca (NY): Cornell University Press.

Broley CL. 1947. Migration and nesting of Florida bald eagles. Wilson Bulletin 59: 3–20.

Broun M. 1935. A Pennsylvania sanctuary for birds of prey. Bulletin of the Massachusetts Audubon Society (January): 3–7.

———. 1939. Fall migration of hawks at Hawk Mountain, Pennsylvania. The Auk 58: 429–441.

———. 1949. Hawks Aloft: The Story of Hawk Mountain. New York: Dodd, Mead.

Brown JH, Heske EJ. 1990. Control of a desert-grassland transition by a keystone rodent guild. Science 250: 1705–1707.

Cade TJ, Enderson JH, Thelander CG, White CM, eds. 1988. Peregrine Falcon Populations: Their Management and Recovery. Boise (ID): Peregrine Fund.

Cade WH. 1975. Acoustically orienting parasitoids: Fly phonotaxis to cricket song. Science 190: 1312–1313.

Carson R. 1962. Silent Spring. Boston: Houghton Mifflin.

Childs JE, et al. 1994. Serologic and genetic identification of *Peromyscus maniculatus* as the primary rodent reservoir for a new hantavirus in the southwestern United States. Journal of Infectious Diseases 169: 1271–1280.

Cissel JH, Swanson FJ, McKee WA, Burditt AL. 1994. Using the past to plan the future in the Pacific Northwest. Journal of Forestry 92: 30–31.

Clark DA. 2004. Tropical forests and global warming: Slowing it down or speeding it up? Frontiers in Ecology and Environment 2: 73–80.

Clifton KE. 1997. Mass spawning by green algae on coral reefs. Science 275: 1116–1118.

Colburn T, vom Saal FS, Soto AM. 1993. Developmental effects of endocrine-disrupting chemicals in wildlife and humans. Environmental Health Perspectives 101: 378–384.

Colburn T, Dumanoski D, Myers JP. 1996. Our Stolen Future: Are We Threatening Our Fertility, Intelligence and Survival? A Scientific Detective Story. New York: Plume/Penguin.

DiMenna MA, Bueno R, Parmenter RR, Norris DE, Sheyka JM, Molina JL, LaBeau EM, Hatton ES, Glass GE. 2006a. The emergence of West Nile virus in mosquito (Diptera: Culicidae) communities of the New Mexico Rio Grande valley. Journal of Medical Entomology 43: 594–599.

———. 2006b. Comparison of mosquito trapping method efficacy for West Nile virus surveillance in New Mexico. Journal of the American Mosquito Control Association 22: 246–253.

Enright JT, Newman WA, Hessler RR, McGowan JR. 1981. Deep-ocean hydrothermal vent communities. Nature 289: 219–221.

Fleming A. 1929. On the antibacterial action of cultures of a penicillium, with special reference to their use in the isolation of *B. influenzae.* British Journal of Experimental Pathology 10: 226–239.

Franklin JF, Cromack K, Denison W, McKee A, Maser C, Sedell J, Swanson F, Juday G. 1981. Ecological characteristics of old-growth Douglas-fir forests. Portland (OR): US Department of Agriculture Forest Service, Pacific Northwest Forest and Range Experiment Station. General Technical Report PNW-118.

Franklin JF, Perry DA, Schowalter TD, Harmon ME, McKee A, Spies TA. 1989. The importance of ecological diversity in maintaining long-term site productivity. Pages 82–97 in Perry DA, Meurisse R, Thomas B, Miller R, Boyle J, Means J, Sollins P, eds. Maintaining the Long-term Productivity of Pacific Northwest Forest Ecosystems. Portland (OR): Timber Press.

Fuller MR, Mosher J. 1981. Methods of detecting and counting raptors: A review. Studies in Avian Biology 6: 235–246.

Glass GE, et al. 2002. Satellite imagery characterizes local animal reservoir populations of Sin Nombre virus in southwestern United States. Proceedings of the National Academies of Science 99: 16817–16822.

Glass GE, Shields TM, Parmenter RR, Goade D, Mills JN, Cheek J, Cook J, Yates TL. 2006. Predicted hantavirus risk in 2006 for the southwestern U.S. Occasional Papers of the Museum of Texas Tech University 255: 1–16. OP-255. (9 February 2009; *www.nsrl.ttu.edu/publications/opapers/ops/op255.pdf*)

Gregory SV, Swanson FJ, McKee WA, Cummins KW. 1991. An ecosystem perspective of riparian zones. BioScience 41: 540–551.

Haeuber RA, Michener WK. 1998. Policy implications of recent natural and managed floods. BioScience 48: 765–772.

Hargrove WW, Hoffman FM. 2004. The potential of multivariate quantitative methods for delineation and visualization of ecoregions. Environmental Management 34: S39–S60.

Hargrove WW, Pickering J. 1992. Pseudoreplication: A sine qua non for regional ecology. Landscape Ecology 6: 251–258.

Hargrove WW, Hoffman FM, Law BE. 2003. New analysis reveals representativeness of the AmeriFlux Network. Eos 84: 529–535.

Hjelle B, Glass GE. 2002. Outbreak of hantavirus infection in the Four Corners region of the United States in the wake of the 1997–1998 El Niño Southern Oscillation. Journal of Infectious Diseases 181: 1569–1573.

Horgan J. 1993. Were Four Corners victims biowar casualties? Scientific American (November): 16.

Jones CG, Ostfeld RS, Richard MP, Schauber EM, Wolff JO. 1998. Chain reactions linking acorns to gypsy moth outbreaks and Lyme disease risk. Science 279: 1023–1026.

Krajick K. 1999. Scientists—and climbers—discover cliff ecosystems. Science 283: 1623–1625.

Kupferberg SJ. 1996. Hydrologic and geomorphic factors affecting conservation of a river-breeding frog (*Rana boylii*). Ecological Applications 6: 1332–1344.

Kupferberg SJ, Lind A, Mount J, Yarnell S. 2008. Pulsed Flow Effects on the Foothill Yellow-Legged Frog (*Rana boylii*): Integration of Empirical, Experimental and Hydrodynamic Modeling Approaches, First Year Interim Report. Sacramento (CA): California Energy Commission.

Likens GE, ed. 1989. Long-term Studies in Ecology. New York: Springer.

Magnuson JJ. 1990. Long-term ecological research and the invisible present. BioScience 40: 495–501.

McKee A. 1998. H. J. Andrews Experimental Forest. Bulletin Ecological Society of America 79: 241–246.

Medawar P. 1984. The Limits of Science. Oxford (United Kingdom): Oxford University Press.

Metchnikoff E. 1901. L'immunitie dans les maladies infectieuses. Paris: Masson.

Myrberg AA. 1996. Fish bioacoustics: Serendipity in research. Bioacoustics 7: 143–150.

Nash DFM, et al. 2002. The outbreak of West Nile virus in the New York City area in 1999. New England Journal of Medicine 344: 1807–1814.

Nichol ST, Spiropoulou CF, Morzunov S, Rollin PE, Ksiazek TG, Feldmann H, Sanchez A, Childs J, Zaki S, Peters CJ. 1993. Genetic identification of a hantavirus associated with an outbreak of acute respiratory illness. Science 262: 914–917.

Norris V. 1995. Hypotheses and the regulation of the bacterial cell cycle. Molecular Microbiology 15: 785–787.

Parmenter RR, Brunt JW, Moore DI, Ernest S. 1993. The Hantavirus Epidemic in the Southwest: Rodent Population Dynamics and the Implications for Transmission of Hantavirus-associated Adult Respiratory Distress Syndrome (HARDS) in the Four Corners Region. Report to the Federal Centers for Disease Control and Prevention, Atlanta, GA. Albuquerque (NM): Sevilleta LTER. SEV publication no. 41.

Peters DPC, Groffman PM, Nadelhoffer KJ, Grimm NB, Collins SL, Michener WK, Huston MA. 2008. Living in an increasingly connected world: A framework for continental-scale environmental science. Frontiers in Ecology and the Environment 6: 229–237.

Peterson RT. 1934. A Field Guide to the Birds. Boston: Houghton Mifflin.

Pfennig DW, Loeb MLG, Collins JP. 1991. Pathogens as a factor limiting the spread of cannibalism in tiger salamanders. Oecologia 88: 161–166.

Ratcliffe DA. 1967. Decrease in eggshell weight in certain birds of prey. Nature 215: 208–210.

Sánchez-Azofeifa G, Daily GC, Pfaff ASP, Busch C. 2003. Integrity and isolation of Costa Rica's national parks and biological reserves: Examining the dynamics of land-cover change. Biological Conservation 109: 123–135.

Smyth JD. 1990. Parasitological serendipity: From *Schistocephalus* to *Echinococcus*. International Journal for Parasitology 20: 411–423.

Thomas JW. 1996. Forest Service perspective on ecosystem management. Ecological Applications 6: 703–705.

[USFS] US Forest Service. 1994. Record of Decision for Amendments to Forest Service and Bureau of Land Management Planning Documents within the Range of the Northern Spotted Owl. (9 February 2009; *www.reo.gov/library/reports/newroda.pdf*)

Whitesell S, Lilieholm RJ, Sharik TL. 2002. A global survey of tropical biological field stations. BioScience 52: 55–64.

Whitfield SM, Bell KE, Philippi T, Sasa M, Bolaños-Vives F, Chaves-Cordero GA, Savage JM, Donnelly MA. 2007. Amphibian and reptile declines over 35 years at La Selva, Costa Rica. Proceedings of the National Academy of Sciences 104: 8352–8356.

Yates TL, et al. 2002. The ecology and evolutionary history of an emergent disease: Hantavirus pulmonary syndrome. BioScience 52: 989–998.

Yoo K, Gibbons C, Su QT, Miles RN, Tien NC. 2002. Fabrication of biomimetic 3-D structured diaphragms. Sensors and Actuators A: Physical 97: 448–456.

William K. Michener (e-mail: wmichener@LTERnet.edu) is with the LTER Network Office and the Department of Biology at the University of New Mexico in Albuquerque. Keith L. Bildstein is Sarkis Acopian Director of Conservation Science at the Acopian Center for Conservation Science in Orwigsburg, Pennsylvania. Arthur McKee is a research scientist with the Flathead Lake Biological Station, University of Montana, Polson. Robert R. Parmenter is chief scientist with Valles Caldera National Preserve in Jemez Springs, New Mexico. William W. Hargrove is an ecologist with the Eastern Forest Threat Assessment Center, USDA Forest Service, Asheville, North Carolina. Deedra McClearn is in Lemont, Pennsylvania. Mark Stromberg is director of the Hastings Natural History Reserve, UC Berkeley Natural History Museums, in Carmel Valley, California.