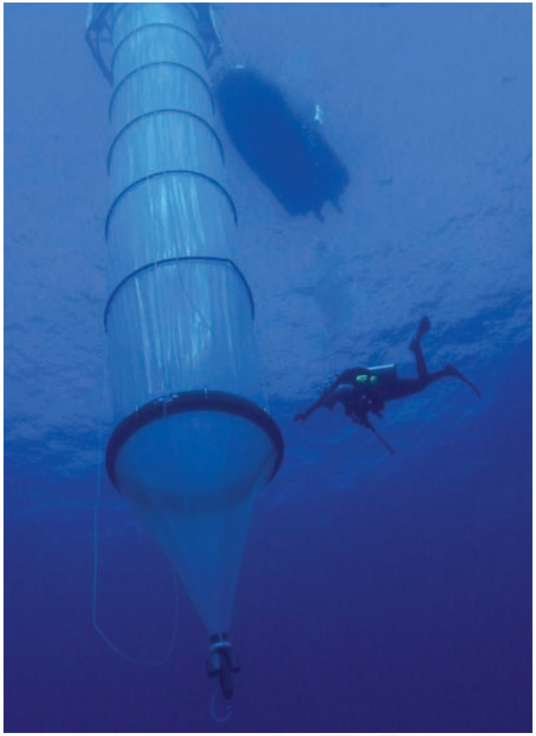
Field Stations and Marine Laboratories of the Future: A Strategic Vision



Field Stations and Marine Laboratories of the Future: A Strategic Vision

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Cover page, clockwise from top left: Broad-tailed hummingbird (Rocky Mountain Biological Laboratory), long-term experiment on biodiversity and ecosystem function (Cedar Creek Ecosystem Science Reserve), KOSMOS off-shore mesocosm, GEOMAR (David Pence), Jepson Prairie Reserve (Dan Cheatham), Bodega Marine Laboratory and Reserve (University of California Natural Reserve System), sampling snow pack to analyze mercury deposition at Mountain Studies Institute in Colorado (Koren Nydick).

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EXECUTIVE SUMMARY

Dealing with dramatic and global environmental change is the challenge of our generation. Rising seas, fire, drought, and flood threaten not only human lives and cities but also the underlying environmental processes that make those lives and cities possible. Biological field stations and marine laboratories (FSMLs) place scientists on the front lines of understanding and managing environmental change. The more than 500 FSMLs around the world, and the long-term records they maintain, make it possible to study environmental processes at multiple spatial and temporal scales. These institutions together represent a standing investment on the order of billions of dollars in tangible assets such as land, buildings, and equipment, as well as intangible assets such as social networks, experience, and knowledge. FSMLs are an enormous—and complex—resource, and require planning to meet ever-changing needs.

The National Association of Marine Laboratories (NAML) and the Organization of Biological Field Stations (OBFS) generated this report to help FSMLs anticipate and prepare for emerging trends in environmental science, education, and stewardship. Guided by seven of their current and past presidents, and with broad input from the community, NAML and OBFS identified emerging scientific trends, the current capacity of FSMLs to address these trends, and key investments that would maximize the unique value of FSMLs in the United States.

FSMLs serve a number of critical scientific functions. They give researchers reliable access to the environment. They accumulate and integrate multidisciplinary, place-based knowledge that provides a baseline from which to evaluate environmental change, as well as the context with which to interpret that change and predict how biological systems may respond to it in the future. FSMLs are hotbeds of innovation. They provide platforms for development, testing, and deployment of sensing technology, and support programs such as the National Ecological Observatory Network and the Ocean Observatories Initiative. They also transform the lives of students of all ages and serve as training grounds for the next generation of scientific leaders. Because many FSMLs are embedded within local communities, they are on the front lines of integrating science into decision-making and of communicating science to the general public.

Based on emerging scientific trends and the roles that field stations and marine labs play in research, education, and stewardship, this report recommends the following goals to guide the future of FSMLs: (1) increase the value to society of the science done at FMSLs, and ensure public understanding of that value; (2) augment the scientific value of FSMLs by increasing the flow of information, both between FSMLs and scientists and among FSMLs themselves; (3) enhance the synergies between research and education; (4) promote appropriate access by scientists and students to terrestrial, aquatic, and marine systems; and (5) improve the operational effectiveness of FSMLs.

To achieve these goals, **we recommend the creation of a national Network Center**. This Network Center will provide the resources, expertise, and continuity to maximize the value of institutions fostering place-based research; strengthen the pathways linking fundamental research and public benefit; identify and enhance elements of FSMLs that have significant impacts on science education; coordinate with federal agencies to ensure continuing access to public lands; and develop a program to train key personnel at field stations and marine labs.

INTRODUCTION

Society depends upon the environment. Natural ecosystems provide services that human beings need and that have great economic value, from purifying water to pollinating crops to regulating climate. Two-thirds of these ecosystem services are in decline around the world (Millennium Ecosystem Assessment 2005). As the population grows and natural resource consumption increases, understanding and sustaining the biodiversity and ecosystem processes that support civilization becomes ever more urgent (NRC 1999, 2001, 2004, 2012; NSF 2009).

The need to observe, predict, manage, and adapt to a rapidly changing environment underpins many of the grand challenges in biology (NRC Grand Challenges 2001, Schwenk et al. 2009, Sutherland 2009, Reid et al. 2010). Policy makers are actively seeking sound science to steward critical environmental resources (e.g., Interagency Ocean Policy Task Force 2010, PCAST 2011, IPBES 2012), and an engaged public demands clear communication about the policy decisions.

Field stations and marine laboratories (FSMLs), which enable ongoing research embedded in the environment, are a tremendous resource for addressing many of these challenges. With a diversity of funding sources, including federal and state monies, support from colleges and universities, private foundations, and individual donors, they provide flexible and cost effective opportunities for scientists to observe environmental processes that occur on a staggering range of spatial and temporal scales. As institutions that bring together researchers from different scientific fields around common problems, FSMLs are a critical part of the infrastructure the nation needs to address a wide range of environmental issues (Wilson 1982, NRC 2001, NSF BIO/DBI Committee of Visitors Report 2007).

Purpose of the Report

This report was developed by the Organization of Biological Field Stations (OBFS) and the National Association of Marine Laboratories (NAML) to help field stations and marine laboratories anticipate and prepare for the future needs of science and society. With approximately 500 FSMLs distributed around the world (including all 50 U.S. states)—and with many individual FSMLs managing a large amount of scientific infrastructure including research vessels, laboratories, living accommodations, and land—there is already a huge existing investment in the FSML network. Because of the diversity, complexity, and enduring nature of field stations and marine laboratories, strategic planning helps ensure that such institutions are well positioned to meet the dynamic and changing needs of scientists, students, and the public they serve.

A steering committee comprised of current and past Presidents of OBFS and NAML—Dr. Ian Billick (Chair), Ivar Babb, Dr. Jan Hodder, Dr. Brian Kloeppel, Dr. Jo-Ann Leong, Dr. Jim Sanders, and Dr. Hilary Swain—oversaw both a workshop including 62 participants (NAML and OBFS 2013a) and a survey of more than 200 FSMLs. Using this information, and with feedback from the larger FSML and scientific community, we address the following questions in this report:

1. What are the critical emerging issues in environmental science, education, and stewardship? To which of these issues can field stations and marine labs make substantial contributions?
2. Which research areas would benefit from greater collaboration and networking among FSMLs?
3. Which components of FSMLs (e.g., laboratory equipment, cyberinfrastructure, research vessels, housing, environmental sensors) most enhance their ability to benefit science and society?
4. What is the current status of these infrastructure components?
5. What investments in FSMLs will yield the greatest returns for science, education, and stewardship?
6. What management and operations practices would most enhance FSMLs' ability to benefit science and society?

This report is intended for use by field station and marine lab personnel in making decisions about where to invest, and in communicating to host institutions and external funding agencies the importance of supporting their FSMLs; by networks of FSMLs to prioritize support for individual facilities; by scientists to help them think creatively about research opportunities; and by educators, resources managers, and others who collaborate with FSMLs to efficiently leverage shared resources.

We begin by defining FSMLs in terms of their scientific capacity, and by surveying emerging trends in biological field research. The following section discusses the unique aspects of education and outreach activities at FSMLs. Next we consider the role of FSMLs in environmental stewardship—the translation of scientific knowledge into policy decisions and natural resource management practices. The report closes with a set of recommendations directed to the FSML community, policy makers, and funders on goals and actions that would help maximize the unique value of field stations and marine labs.

As we address these questions, we anchor our report in real-world examples of field station and marine lab successes and impacts, with attention to the current status of their infrastructure and to the ways FSMLs both function within and complement the nation's larger portfolio of assets directed towards understanding the environment.

What are FSMLs?

Field stations and marine laboratories (FSMLs) are centers of scientific research embedded in the environment, places where scientists have developed, over many years, an intimate understanding of the natural processes that support human life. They are living laboratories, vast libraries of environmental knowledge where the interactions among the actors—including humans—have been examined and cataloged, and people come every day to ask new questions.

Historically, institutions have self-defined as field stations or marine labs based primarily on shared administrative structures, facility types, or peer networks. In this report, however, ***we use a very broad definition of FSML that emerges from the science of working in the field.***

We define FSMLs as facilities or institutions that facilitate a significant amount of research (1) with a geographic focus, although the geographic focus may be very complex and involve access to widely distributed sites in addition to core areas; (2) on environmental processes, though we recognize that similar institutions may exist to serve other scientific disciplines; and (3) by multiple research groups, over sustained periods of time. Field stations and marine labs serve as platforms for multiple scientists and are not solely a vehicle for the research efforts of a single research team. They also support a range of activities leveraging that research such as education, outreach, and stewardship. Using a broader definition of FSML allows us to focus on the science of place-based research rather than on organizational boundaries.


Douglas Peebles

istockphoto/Joellen Fonken

Scientists delve into ecosystems of all kinds at field stations and marine labs. The Hawaiʻi Institute of Marine Biology (left) aims to understand and conserve tropical marine environments. The Central Arizona Phoenix Long-Term Ecological Research project (right) focuses on an arid land ecosystem profoundly influenced by human activities.

What FSMLs Do for Science and Society

The environment is everywhere, but the means to study it are not. Field stations and marine labs bring the basic tools of science—from electricity to community—to the places where science needs to be done, and cultivate a base of place-specific knowledge that fosters discovery. Field research in a wide range of disciplines, including the environmental sciences, ecology, and evolutionary biology, relies on FSMLs.

Managing scientific resources for long-term sustainability requires an understanding of the unique benefit they provide (ESA 2011). Using our definition of FSMLs as facilities that support sustained place-based research on environmental processes, we identify four primary functions that FSMLs serve:

1. They provide ***access*** to the environment.
2. They provide ***logistical support*** for a wide range of activities including individual research projects; networking of research on larger scales; science, technology, engineering, and mathematics (STEM) training; and public outreach.
3. Through time they become ***model ecosystems*** in which the steady accumulation of site-specific knowledge becomes a powerful platform for future research.
4. They foster a ***community of scholars*** that promotes the exchange of ideas, collaboration, and the integration of knowledge, and can facilitate the flow of information between the scientific community and decision makers about environmental issues.

Access

Historically, FSMLs have been important primarily because they provide convenient access to relatively natural environments. Initially there was a focus on the collection of fresh biological material for analysis. As ecology and related disciplines emerged in the early 1900s, the emphasis on collecting shifted to studying organisms in their natural environment, and to understanding other environmental processes that were best observed in the field (see Box 1).

Box 1. Science in the Wild

Laboratories alone rarely tell the whole story. Genes, organisms, and populations all respond differently to complex natural environments than to controlled laboratory ones. The DNA that controls when a plant flowers in the lab is not the same DNA that controls it in the field (Wilczek et al. 2009, Brachi et al. 2010, Anderson et al. 2011); how tadpoles compete in the lab may not predict who wins in the field (Melvin and Houlahan 2012). To study environmental processes, it pays to be in the environment.

FSMLs continue to provide scientists access to land, ocean, and coastal waters, and they do it in a variety of ways. The survey conducted as part of the planning process (NAML and OBFS 2013b) found that almost as many FSMLs provide access to public lands through the relevant permit (71%) as provide access to property they own (73%). Access to privately owned land is also important: 54% of FSMLs have agreements with private landowners. FSMLs also help ensure access to research sites by maintaining vehicles, research vessels, and docks. For long-term research, long-term access is critical (Bildstein and Brisbin 1990); as institutions, FSMLs can maintain the long-term relationships that ensure regular and reliable access to research sites.

FSMLs also provide security for sites. They facilitate reliable long-term research by either removing research sites from public access or educating the public about how they might move through areas with research sites in a way that minimizes impacts on the local environment and the research. At the same time, they provide a point of entry for the general public, both to the environment itself and to the scientific advancement occurring at the field station or marine lab.

Logistical Support

FSMLs take care of the details so that scientists and students can work effectively in the field. FSMLs provide logistical support in many ways (see Box 2 on page 7), including providing appropriate telecommunications to support data collection, management of hazardous materials, physical facilities to support the deployment of large or complex equipment into the field sites, appropriate transportation to reach research sites (e.g., research vessels, four-wheel drive vehicles), or facilities to store or work on equipment when it is not deployed. The support may also include housing,

Field stations and marine labs

Education


Craig Young

Faculty and graduate students live and work year round at the Oregon Institute of Marine Biology, conducting experiments and facilitating undergraduate education both in the lab and out on the open ocean. Each of the hundred biology majors at the University of Oregon spends three academic quarters on the coast, taking courses and doing original research. The residential program fosters student-centered learning in ways that are impossible on the main campus, where classes are limited to 50-minute lectures or prescribed lab periods. Students often spend an entire day or more working with senior scientists on a single project, and can integrate the disciplines of biology across a group of organisms.

Research


RMBL

Buried under snow three-quarters of the year, the high-elevation Rocky Mountain Biological Laboratory (RMBL) in Colorado supports one of the largest annual migrations of field biologists in the summertime. RMBL is a nonprofit field station built around the log cabins of an abandoned mining town and surrounded by National Forest. One scientist there has been monitoring flowering plants' timing for forty years; others follow the butterflies or the marmots; a year-round staffer has recorded the date of snowmelt every spring since 1975. These long-term datasets come together in unique and important ways to provide a window on biological responses to climate change.

Partnership


NOAA

The Hollings Marine Laboratory (HML) in Charleston, South Carolina promotes interdisciplinary research from molecules to ecosystems through the sharing of expertise, specialized equipment, space, and other resources. Operated by the National Oceanic and Atmospheric Administration (NOAA) in partnership with both academic institutions and other federal and state agencies, the HML is equipped with state-of-the-art analytical instrumentation to identify and quantify pollutants, toxicants, and pathogens; Level 2+ biosafety laboratories; seawater systems and aquaculture facilities; a nuclear magnetic resonance facility (left); an ecological field collection launching and sample preparation area; a cryogenic specimen bank; and one of the nation's leading genomic laboratories devoted to marine species. The HML's scientists collaborate to sustain, protect and restore coastal ecosystems, and to safeguard human health.

Place


Brian Helmuth

Tatoosh Island, off the coast of Washington State, is a remote former coast guard station and a whaling base for the Makah tribe. In the 1960s, a researcher started looking at intertidal species here; his discoveries attracted more researchers. There is no institutional support for the site, but scientists return year after year to haul their own water, sleep in bunk beds, and foster a deep knowledge of place. Ecological theory developed in the rocky intertidal on Tatoosh underpins our understanding of ecosystems as far removed as the high desert scrub. Decades of continuous research on the island are now revealing disturbing changes: There are half as many gulls as there were ten years ago; mussel shells are getting noticeably thinner. The changes may serve as advanced warning of what happens when the ocean's acidity rises—which it is doing, around the island, ten times faster than accepted climate models predict (Solie 2012).

research laboratory space, maintenance of sensors, equipment that enables exploration of unique environments (e.g., underwater vehicles, diving support, or canopy towers), calibration and validation of sensors, and mesocosms for experimentation.

The relative importance of different elements of infrastructure provided by FSMLs depends on the particular situation, but some recurring themes nevertheless emerge from the survey. More than 80% of FSMLs indicate that electricity, internet access, and support staff are critical elements of their infrastructure, with more than 60% citing laboratory space, storage, long-term monitoring, and classrooms. Onsite housing was cited by 59% of FSMLs as being critical.

The importance of the human capital at FSMLs in providing logistical support for research should not be underestimated. Doing field research often requires considerable technical expertise gained through long experience, e.g., the operation of large research vessels. Because scientists often have distinctive and highly technical objectives, project teams often require a unique combination of technical and research expertise that can only be developed through experience.

Accumulated expertise includes not only the technical know-how to deploy complex instrumentation in the field, but also the fundamental natural history knowledge required to design and interpret studies (e.g., Simons 2011). Field studies regularly rely on such knowledge to find an organism or particular habitat type, to collect data in a meaningful way, and for information about the phenology of that organism. Such information can save researchers entire field seasons and provide sufficient contextual information to correctly interpret results.


Jeffrey Dukes

Box 2. Open-Air Experiment

The Jasper Ridge Global Change Experiment teases apart the interacting effects of multiple changing factors on a California grassland ecosystem. This paradigm-changing research would not have been possible without the support of a very good field station over the past twenty years. It takes plumbing and electricity to run an experiment in a wild, open field; it takes long-term relationships with local fire crews and pest management districts to agree on a land use plan. Because the site is protected, researchers can construct elaborate outdoor infrastructure. Because the site's species and local ecology have been intensively studied, researchers can interpret results in the proper context. And by comparing their findings with those from dozens of other field stations, researchers can better predict how ecosystems around the world will respond to global change.

FSMLs create a bridge between natural environments and research laboratories. Research laboratories offer considerable power to analyze specimens in a clean and predictable environment and to infer cause and effect from manipulative experiments, but they may miss factors that turn out to be critical in a natural environment (see Box 1 on page 5). Field studies can encompass the full range of relevant interactions and scales, but they are not as tightly controlled. By offering access to both laboratories and field environments, FSMLs combine the best of both worlds. Furthermore, the use of mesocosms—including artificial streams, ponds, gardens, and environmental chambers—allows scientists to finely tune the extent to which they combine the controlled setting of a lab with the natural environmental context (see Box 18 on page 27).

FSMLs often play a critical logistical role in allowing studies to extend across decades. For example, FSMLs can provide the infrastructure that makes it feasible for a single individual to collect data throughout a lifetime, and can even facilitate the maintenance of meaningful data streams that extend beyond the career of a single scientist (see Box 3).

Such institutional capacity is critical for data streams from automated sensors. Because of the combination of technical support and expertise, logistical support, and access to a range of environmental conditions, FSMLs often are a hotbed of sensor development (Porter et al. 2009). Once a new sensor has been developed, they are often deployed at FSMLs for the same reasons. Furthermore, on the scale of decades, technology has been changing rapidly enough that considerable human expertise is required to maintain a level of standardization that ensures such data can be interpreted even as protocols change in response to improving technology.

FSMLs also provide support for work done primarily in laboratories. Indeed, establishment of the early marine labs was driven in part by the desire to efficiently gather specimens for examination under microscopes. More recently, as scientists have begun to explore gene regulation under natural environmental conditions, the specimens they gather require sequencers and microarrays. FSMLs can provide access to ultra cold freezers or liquid nitrogen to preserve RNA and other quickly degrading molecules for later analysis in the lab.

Increasingly, FSMLs are playing an important logistical role in supporting networks that extend beyond any single FSML. Because environmental processes occur on a wide range of spatial and temporal scales, data streams are standardized and networked to varying degrees to facilitate cross-site and long-term analyses. FSMLs form the backbone of the Long Term Ecological Research (LTER) program, serve as both core and satellite

Box 3. On the Shoulders of Ornithologists

The longest-running continuous bird study in North America focuses on the Florida Scrub-jay, *Aphelocoma coerulescens*. Begun in 1969 at Archbold Biological Station, research on this threatened species has grown to encompass approaches from behavioral ecology and evolutionary biology to endocrinology and functional genomics, and now outlives its founder (Woolfenden and Fitzpatrick 1984). This body of knowledge helped Archbold scientists spearhead conservation planning for scrub-jays that serves as a model for bird conservation worldwide.


Teva Sylvain

Box 4. Model Ecosystem

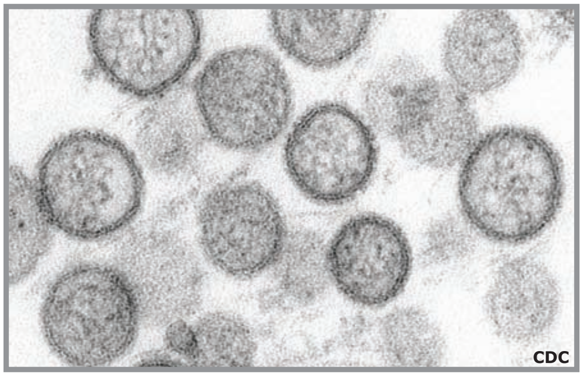
A South Pacific island about the size of San Francisco may be the world's most fully characterized model ecosystem. Scientists have studied Moorea from the coral reefs to the cloud forest for 40 years, and are now cataloguing DNA from every species on the island (Eichenseher 2011), which is increasingly wired with sensor networks for real-time monitoring of temperature, current patterns, and other variables (Fountain et al. 2009). Being able to track every interacting component will allow ecologists to reconstruct energy flows through the entire ecosystem; understand changes in biodiversity and ecosystem function in response to invasive organisms, climate change, and pollution; and help increase the resilience of ecosystems on Moorea and beyond.

sites for the National Ecological Observatory Network (NEON), support critical elements of the Ocean Observatories Initiative (OOI) and University-National Oceanographic Laboratory System (UNOLS), and host any number of other networked data streams such as the National Atmospheric Deposition Program (NADP) network, the Global Lake Ecological Observatory Network (GLEON), and the Integrated Ocean Observing System (IOOS).

Model Ecosystems

More recently, FSMLs have developed additional value because of their accumulation of site-specific knowledge (Billick and Price 2010). Given the complexity and interconnected nature of many environmental processes, FSMLs provide opportunities to weave together the work of many scientists in order to see patterns and understand processes that would not be apparent from any single study or data stream. While it is often logistical considerations that attract scientists to a new facility, eventually sites develop a body of knowledge that becomes a powerful platform for supporting additional research (see Box 4). Knowledge begets knowledge (Wilson 1982, Price and Billick 2010) and the area around an FSML becomes a model ecosystem (Aigner and Koehler 2010).

Scientists use this body of information to contextualize individual studies, extend the work of others, combine separate studies in order to detect complex processes (see Box 5), and take advantage of long-term studies to investigate processes that cannot be observed on short time scales (e.g., Ozgul et al. 2010). The importance of this to field science is typified by the increasing complexity of data streams associated with individual sites, including long-term experiments, automated sensors, natural history collections, and genetic data. The ability to combine multiple data streams associated with a single location provides scientific opportunities that would not be available if those data streams were each generated from a different location.



CDC

Box 5. Hunting Hantavirus

When a deadly disease emerged in the American southwest in 1993, a nearby field station was able to explain the epidemic. It was an unknown strain of hantavirus–never before identified in North America–carried by deer mice that scientists at the Sevilleta Long Term Ecological Research project happened to have begun studying five years earlier. Sevilleta research revealed that El Niño weather patterns control population densities of deer mice; historical data from Canyonlands National Park confirmed it. Meanwhile, twenty-year-old mouse tissue archived at the Museum of Southwestern Biology showed that the virus was not actually new, at least not to mice. By understanding the ecology of the hantavirus host, scientists have been able to predict outbreaks of the disease and warn the public at times of increased risk (Michener et al. 2009)

Communities of Scholars

Perhaps the most critical element of a research station is the community of scholars that develops. Legendary innovation has arisen out of highly interactive environments like Bell Labs (Gertner 2012) or MIT's Building 20 (Lehrer 2012). Scientists coming together around the same ecosystem likewise have rich opportunities to exchange ideas and information, leading to many serendipitous discoveries (Michener et al. 2009). When the location binds together multiple scientists, disciplines, and datastreams, synergies emerge.

These synergies also emerge from the integration of research and training. Students identify new questions; develop the natural history, research, and technical skills needed to enable future research; and develop the science skills that allow for a highly productive workforce and scientifically literate citizenry. In turn, time at an FSML is often highly motivational for students. They interact with scientists in research teams, have the freedom to explore, and move along the continuum from passive learners to active scientists.

Box 6. Citizen Science

Citizen scientists—sailors, kayakers, surfers, and beach walkers—are the eyes and ears of the coast. A seventh grader can tell a European green crab from an Asian shore crab; a sophomore in college can tell a male crab from a female one (Delaney et al. 2008). In a McGill University project funded by NOAA's National Sea Grant program, citizen scientists from New Jersey to Maine detected an invasive crab species expanding its range, and collected enough data to make possible a model to predict its spread.

Communication and information flow at FSMLs ideally extends beyond the community of scholars. Common interests in the local environment provide an opportunity for dynamic interplay between various stakeholders, including FSML scientists, natural resource managers, policy makers, and citizens (see Box 6).

Diversity of FSMLs

The survey conducted as part of this planning process (NAML and OBFS 2013b) demonstrates the variety and extent of the FSML network (see Figure 1). While there is no single reliable inventory of all FSMLs, we were able to identify and contact 444 institutions, of which 227 responded. Our respondents were an unbiased sample of the institutions in our list with respect to size, host institution, and whether the facility serves marine research or not.

This survey indicated that 65% of U.S. FSMLs are field stations that serve research solely on terrestrial and freshwater systems. The remaining facilities support some level of marine research, including estuary research. Three-quarters of FSMLs are organized as part of a college or university, 16% operate as part of a federal or state agency, and the remaining facilities operate as a stand-alone non-profit or part of a larger non-profit. The bulk of these institutions serve research scientists (97%), graduate students (93%), and undergraduates (92%), with a significant number also serving K-12 education (66%), the general public (66%), state scientists (65%), and federal scientists (62%). FSMLs commonly partner with other organizations: 88% report collaborations with research institutions, 85% with state agencies, 82% with federal agencies, 71% with non-governmental organizations, and 54% with other FSMLs.

FSMLs provide access to research sites using a variety of mechanisms including property owned by the FSML (72%), a permit providing access to public lands (71%), land managed though not owned by FSMLs (69%), and arrangements with private landowners (54%).

FSMLs vary considerably in size. Most FSMLs (60%) reported maintaining 1–10 full-time staff equivalents. Eight percent indicate they have 0 FTEs, and 2% indicate they have between 250 and 500 FTEs. A station director was the most common employee at a site (73% reported having such an individual), with maintenance staff (62%), office staff (51%), and research technicians (49%) also being common. In terms of budgets, annual expenditures are commonly between $250,000 and $5 million (47%), though 17% of FSMLs reported annual finances of less than $50,000 and 4% indicated annual expenses of more than $15 million.

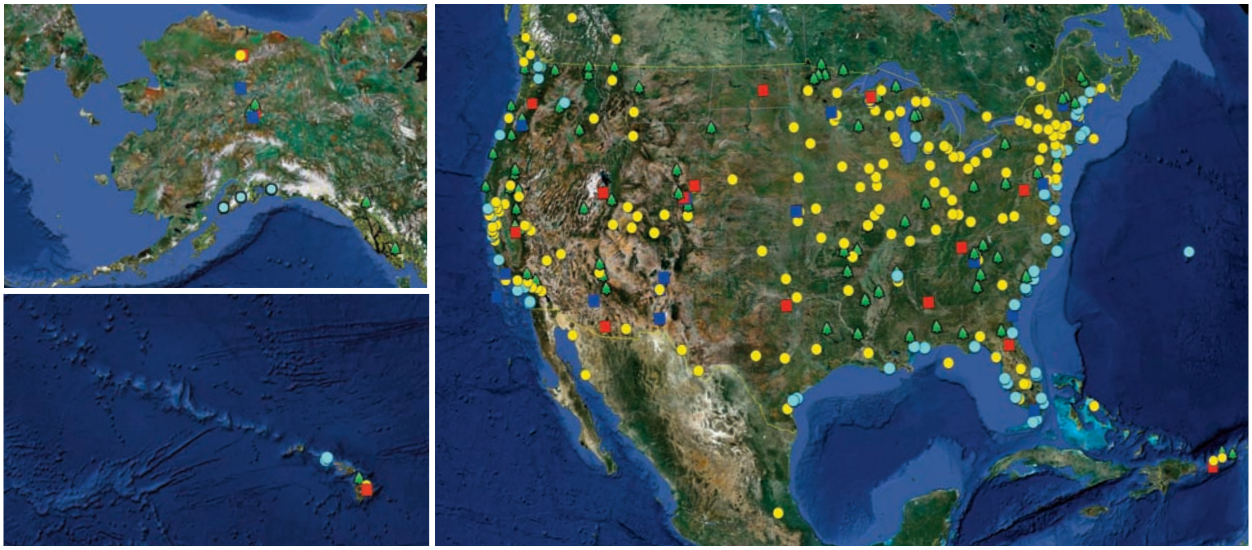
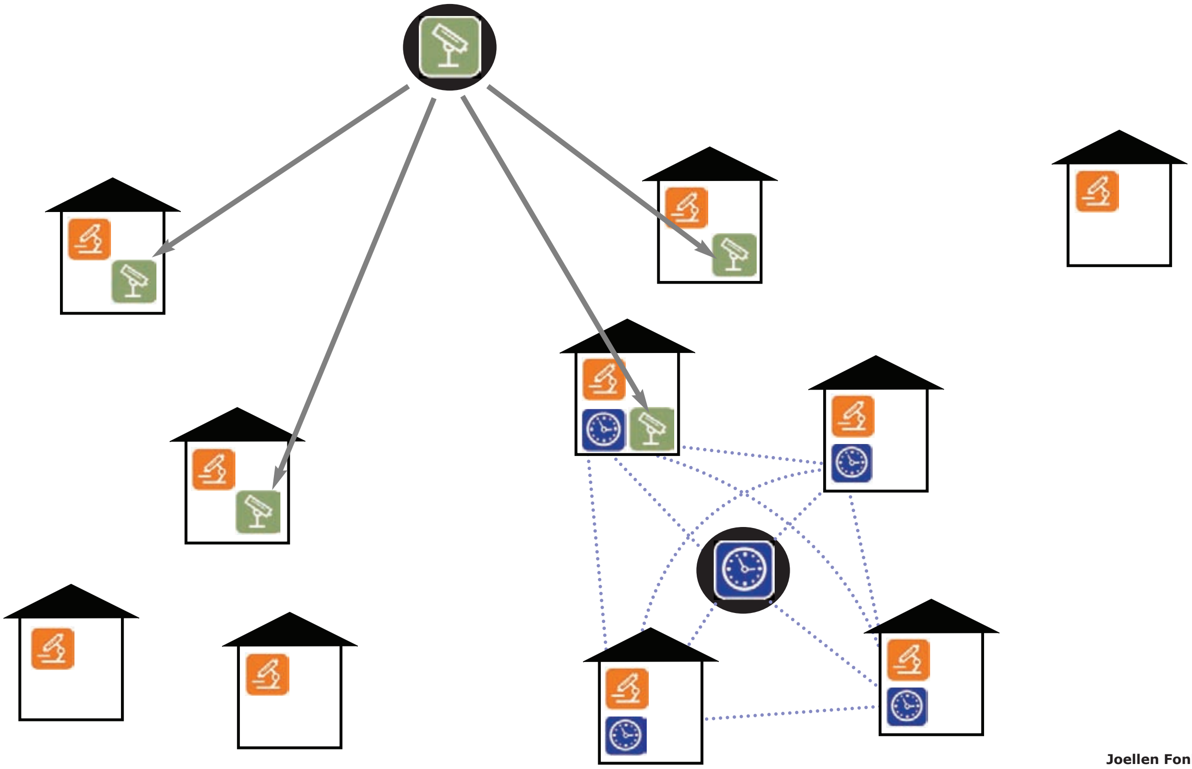


Figure 1. United States field station and marine lab networks include the Organization of Biological Field Stations (🟡), the National Association of Marine Labs (🔵), the USDA Forest Service Experimental Forests and Ranges (🌲), the National Ecological Observatory Network (🟥), and the Long-Term Ecological Research network (🟦). These organizations often share sites and facilities.

These summary statistics reveal an incredible diversity within the FSML community. A field station or marine lab may be a piece of land owned by a university that has been used by scientists and students over extended periods of time despite the complete absence of any associated facilities; or it may consist of an extensive physical plant—including dormitories, research vessels, research labs, and mesocosms—placed on substantial land holdings. Each FSML supports sustained research by multiple groups into the environmental processes of a specific place.

How do FSMLs relate to other ecological networks?

Field stations and marine laboratories are part of a diverse portfolio of assets that the world maintains to support study of the environment—a complex ecosystem of facilities, programs, and networks that complement each other and provide synergistic opportunities (see Figure 2). The research opportunities associated with any one of these assets alone, no matter how large, would be limited. Together, however, they have the potential to integrate broadly distributed sensors and long-term studies with rapidly changing techniques and new studies to generate powerful insights about the environment.



Joellen Fonken

Figure 2. Field stations and marine labs (⌂) support various kinds of discovery. Individual scientists (🔬) work at every FSML. FSMLs also host a variety of programs. Some of these programs (🔭) have topdown control over the science occurring at each station; others (🕒) facilitate collaboration among stations around specific research goals. An example of the former is NEON; an example of the latter is LTER. Other such programs include but are not limited to the Global Lake Ecological Observatory Network, Critical Zone Observatories, Integrated Ocean Observing System, and the Ocean Observatories Initiative.

To examine the relationship between FSMLs and other such entities, we take as examples two recent major ecological observing initiatives. The National Ecological Observatory Network (NEON) is a continental-scale research platform now under construction. NEON is installing observing systems and implementing standardized protocols to facilitate cross-site research on the impacts of climate change, land-use change, and invasive species on terrestrial and aquatic ecology. In similar fashion, the Ocean Observatories Initiative (OOI) is currently building networked sensor systems in the ocean and on the seafloor to improve detection and forecasting of environmental changes and their effects on biodiversity, coastal ecosystems, and climate. The core of these programs are sensors and systems to observe processes in consistent ways across large areas, and both rely to a great extent on infrastructure at FSMLs. For example, FSMLs provided logistical support for the development and testing of many of the sensors, and are hosting deployments of the final implementation.

FSMLs do much more than simply provide logistical support, however. They complement the observing programs and provide synergistic research opportunities that would not be achievable through FSMLs, NEON, or the OOI alone. The continental- and global-scale observations provided by NEON and the OOI will ideally only be a starting point. If the observatories are successful, they will generate new ideas and hypotheses which will require both new technology and opportunities to conduct follow-up studies—many of which may well need to happen outside core NEON installations. The larger network of FSMLs, because of their broad spatial distribution, existing infrastructure, and their ability to adapt to rapidly changing scientific needs, will often be the best place for such work to happen. **While the strength of NEON and the OOI is standardization, the strength of field stations and marine labs is flexibility: FSMLs can accommodate and support novel experimental approaches, and as a group they encompass tremendous ecological diversity**. The accumulated knowledge at each FSML provides an invaluable context for future studies to build on, and a lens on the past of that ecosystem. Both the large-scale perspective of the observatories and the place-based depth of knowledge in the FSML network are necessary to foster a better understanding of the feedbacks between local, regional, and global patterns and processes over the long term.

NEON and the OOI are only two examples of environmental research infrastructure that FSMLs complement. The list of programs, networks, and facilities is too long to list comprehensively, but includes state and federal labs and field sites (e.g., USFS Experimental Forests and Ranges; NOAA's Sentinel Sites and National Marine Fisheries Service; the National Estuarine Research Reserve System; NSF's Critical Zone Observatories; the US National Park Service Inventory and Monitoring Program; Agricultural Experiment Stations; and NASA's Earth Observing System) as well as programs that coordinate data coming out of FSMLs, such as the Long-Term Ecological Research Network and the Global Lake Ecological Observatory Network. All of these entities, including field stations and marine labs, are complementary parts of a global investment in understanding the environment.

EMERGING SCIENTIFIC TRENDS

Positioning FSMLs for the future requires an understanding of what the future has in store for science (ESA 2011). The physical plants, administrative structure, and land-holdings of FSMLs can take years to develop; but the science they support is always innovating.

To generate a perspective on where science is headed, particularly as it relates to FSMLs, we first drew upon a workshop attended by 62 scientists and FSML specialists that met November 17–18, 2011. Prior to and during this workshop, participants discussed where research, education, and environmental stewardship are headed, and the role of FSMLs in serving those future needs (NAML and OBFS 2013a). Second, in a survey of FSMLs we asked what scientific trends respondents have observed (NAML and OBFS 2013b). We summarize observations from the workshop and survey below. Finally, we integrated this information with observations and analysis from the steering committee and generated a list of emerging trends that bear upon field stations.

Trends Identified at the Workshop

Keynote speaker David Schimel, Chief Science Officer at NEON, Inc., highlighted the issue of rapid global change—and in particular, how the speed of change affects science itself. Because ecosystems are no longer in a stable state, the historical data available at FSMLs are increasingly valuable, and are an essential foundation for future models and forecasts. The contextual information available at a well-studied site is also critical, since the outcome of an experiment depends on the state of the system during that experiment. Isolated place-based studies are not enough, however; Schimel emphasized that linking sites to achieve regional and continental scales is crucial.

Peter Stine, the National Coordinator for Experimental Forests and Ranges within the United States Forest Service, also emphasized the importance of understanding long-term change on multiple spatial scales, from local to continental. He indicated that the Experimental Forest system is proposing to use an extensive set of automated sensors to improve their ability to network measurements. A pressing issue for the system is how to deal with data management, including ensuring that the full value of historical data is realized. In addition to change, Stine cited increasing interest in understanding urban ecology, the human uses of natural landscapes, and the integration of social sciences and field research.

Participants in the workshop broke out into five working groups: Molecular Biology and Genomics, Ecosystem Dynamics, Environmental Change, Macrosystems, and Organismal and Population Biology. Emerging trends identified within those groups included a wide range of subjects (NAML and OBFS 2013a).

Three of the groups, Environmental Change, Ecosystem Dynamics, and Macrosystems, focused attention on the grand challenges that have been articulated in recent publications and can be served by FSMLs (NRC 2001, Reid et al. 2010). These include the following:

- the causes and consequences of biological invasions
- biogeochemical cycles with an emphasis on climate-related processes
- land use dynamics and consequences

- biodiversity and ecosystem function
- the ecology of disease
- avoiding and managing disruptive global environmental change

The Macrosystems group also identified a more specific set of emerging issues in which FSMLs play a central role:

- regional- to global-scale quantification of carbon cycling, storage, and dynamic temporal interactions with climate that reveal mechanisms and drivers
- long-term effects of changing climate, land use, and urbanization (over space and time), and their interactions with ecosystem structure and function (e.g. nutrient cycling)
- large-scale patterns of changes in species (native and non-native/invasive) including composition, abundance, genetic diversity and distribution
- methods for evaluating and, where needed, restoring ecological connectivity
- large-scale and multi-temporal changes in the provision of ecosystem services and their implications for socioeconomic systems

The Organismal and Population Biology group identified the following outstanding questions, needs, and issues:

- how organisms, populations, ecosystems, and global societies respond to the rapid and accelerating pace, and increased inter-annual variation, of environmental change
- the links among genes, phenotypes, environment, and fitness
- the ecological context of genomics
- the need to integrate natural and social sciences effectively
- the use of key sentinel species to understand and predict environmental change
- the value of legacy observations in understanding environmental change
- the enduring importance of natural history

Molecular Biology and Genomics generated perhaps the most unique set of emerging issues at the workshop:

- moving beyond documenting genomic diversity to understanding genomic function
- the genomic basis of ecosystem services
- understanding the extent to which bacteria mediate responses of larger organisms to environmental change
- the biogeography of microorganisms
- the ability to use non-model organisms to study gene regulation and transcriptomics in natural environments
- tracking gene expression in response to perturbations in real time
- the importance of discovery-based science, driven by rapidly developing instrumentation
- the emerging need for informaticians
- the importance of embedding genomic information within a larger context

In addition to the syntheses from each of the work groups, a number of other scientific trends came up in discussions. These included the rise in single-cell techniques; the ability to cultivate more micro-organisms in lab settings; the need to track large-scale patterns of changes in species, both native and non-native; methods for evaluating ecological connectivity; understanding how the loss of top predators shapes systems; and understanding phenology, particularly in the context of climate change.

Trends Identified in the Survey

In a very broad-brush coding analysis of open-ended responses to a question about scientific trends observed at FSMLs, climate-related science and technology were the most commonly mentioned scientific trends, with 22% and 21% of respondents citing them, respectively, as important trends. A review of individual comments reveals a number of trends being cited by multiple institutions. These include an increasing interest in understanding global change, an increasing use of molecular techniques in the field, an increasing use of automated sensors, a greater emphasis on data mining, more collaborative research, declining natural history skills, an increasing interest in long-term studies, increasing interest in research on invasive organisms, and increasing interest in working on larger spatial scales and/or cross-site research.

Emerging Scientific Trends to which FSMLs Can Best Contribute

Based on the review of a wide body of information, the steering committee has identified the emerging trends that it believes FSMLs need to facilitate to help move the environmental sciences forward. These emerging trends can be understood as part of an overarching narrative that involves the integration of different types of data streams to develop a stronger understanding of environmental processes. The ability to successfully integrate these data streams requires significant human capacity, both in terms of the expertise to manage large volumes of complex information and the expertise to utilize this information to address complex and/or interdisciplinary problems. Ultimately, these efforts should lead to a greater mechanistic understanding of environmental processes and provide more robust models of climate change and its impacts. The trends described here are not research questions per se, but rather reflect the approaches scientists are commonly using to address emerging issues.

Predicting the Future

The environment is changing faster than it ever has, from ocean acidification to species extinction. Organisms are responding rapidly to climate change (e.g., Walther 2002, Parmesan 2006), leading to potential wide-scale disruption of ecological systems; emerging diseases are a significant and global threat to human health (e.g., Jones et al. 2008); and the economic cost associated with invasive species reaches $120 billion/year (Pimentel et al. 2005).

Ecological science has the potential to predict the consequences of these changes for ecosystems (see Box 7) and for human well-being (LTER 2011), and to identify intervention points to affect outcomes (Reid et al. 2010). For example, a global effort is underway to predict and prevent the spread of diseases emerging from changing land use and


Moorea Coral Reef LTER

Box 7. Resilience of Coral Reefs

Coral reefs off the island of Moorea have survived seastar infestations and devastating cyclones, thanks to herbivorous fishes that keep down the algae until the coral can grow back (Adam et al. 2011). But who protects the herbivorous fish? An ecosystem is only as stable as its weakest link. As long as the network remains intact, the resilience of the network remains intact.

climate (Robbins 2012). As the economic and human health risks of action or inaction increase, the value of reducing uncertainty about the future grows.

Revealing the Past

Environmental processes happen at time scales longer than a typical research grant. Long-term research has always been fundamental to ecology, but interest in long-term processes—and especially in looking back at the past—has increased as understanding global change has become critical. Many fundamental questions can only be addressed by tracking phenomena in the field over extended periods of time (Wilson 1982, Callahan 1984, Strayer et al. 1986, Hobbie et al. 2003, Lindenmayer and Likens 2009, Magurran et al. 2010; see Box 8). Both wise management (Underwood 1995) and conservation (Ehrlich and Murphy 1987, Pullin and Salafsky 2010) depend on access to long-term and widely distributed data (Hunt et al. 2007). Consequently the United States has made significant and increasing investments in enabling research on large temporal and spatial scales, including the establishment of the Long Term Ecological Research (LTER) network (Hobbie et al. 2003, Knapp et al. 2012), the National Ecological Observatory Network (NEON; Pennisi 2010, Schimel et al. 2011), and the Ocean Observatories Initiative (OOI; Isern 2006)—each of which rely to some extent on the infrastructure at field stations and marine labs.


Cedar Creek Ecosystem Science Reserve

Box 8. Just Wait

Ongoing research is critical because the answer you get depends on when you ask the question. In global change experiments, soil microbes that control biogeochemical cycles behave differently in the wintertime (Contosta et al. 2011). Systems can respond slowly to simulated climates, changing completely after four to ten years (Knapp et al. 2012). And the true effect of biodiversity on ecosystem function is only apparent after experiments have been running for more than a decade (Reich et al. 2012).

Crossing Spatial Scales

Most ecological studies are local; organisms interact at short distances, and ecologists can only travel so far in a day. Climate change and other drivers are not as geographically constrained. From the level of the landscape across which fires burn, to the level of the continent across which invasive species spread, emerging scientific questions cover vast expanses (NRC 2003a). Understanding the interplay between processes happening at different scales (see Box 9) is crucial for predicting and managing the future environment (Levin and Clark 2010).

Automated Sensing

There has been an explosion in the development of technology that enables automated data acquisition in the field (Porter et al. 2009, Rundel et al. 2009). Automated sensors track the weather, the movement patterns of marine mammals, and the flow rates of streams. These sensors may be remote, recording planktonic productivity on the surface of the ocean from a satellite in space, or they may be intimately embedded in organisms, recording a shark's last meal from a chip inside its stomach. The sensors may be fixed in a single location, like a data logger tracking the temperature of a marmot den, or they may be on mobile platforms, like an airplane over the rainforest (see Box 10) or an autonomous ocean glider profiling the ocean water column.

This increase in sensing technology is due in part to NSF's investment in the Center for Embedded Network Sensing. This engineering center is dedicated to increasing the number of environmental parameters that can be measured automatically, while maintaining the feasibility of deploying such equipment by dealing with energy and data stream considerations. Importantly, the large investment in NEON and OOI should increase the availability of sensors, as well as make it easier to embed sensor data streams into larger networks.

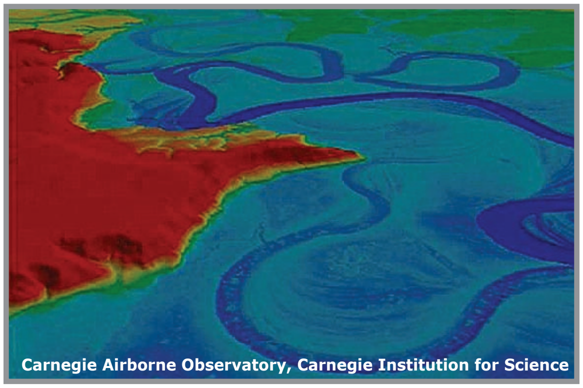
Biodiversity

The diversity of life on Earth controls many of the biophysical properties of the planet, including ecosystem goods and services that are essential to humans (Cardinale 2012, Cardinale et al. 2012). Documenting biodiversity, and understanding how its rapid loss will alter ecosystem function, is an urgent priority being addressed not only at FSMLs—many of which have long-term species occurrence data and collections—but by networks of natural history museums and data management initiatives. The Global Biodiversity Information Facility (GBIF) in particular facilitates collection of and access to information about the distribution of organisms over time and across the planet.

The Group on Earth Observations Biodiversity Observation Network (GEO BON) is currently developing a core set of Essential Biodiversity Variables that could form the basis of monitoring programs across the globe (Pereira et al. 2013). Among the many dimensions of biodiversity—loss of genetic diversity, changes in species abundances, shifts in ranges, species

Box 9. Near vs. Far

Large-scale forces play a pivotal role in determining local species diversity. By sampling sponges, corals and other shallow water ocean invertebrates at sites in 12 distinct biogeographic regions across seven continents, researchers found that the number of species sharing a neighborhood depends not just on the usual nearby suspects—predation and competition, hurricanes and landslides—but also on diversity in the surrounding waters, areas often spanning thousands of square miles (Witman et al. 2004). Initiatives to maintain biodiversity need to take into account both local and regional dynamics.


Carnegie Airborne Observatory, Carnegie Institution for Science

Box 10. High Flying

From a twin-engine airplane over the Amazon, the Carnegie Airborne Observatory can identify individual trees and map branches in the canopy (Asner et al. 2012). The observatory makes it possible to track deforestation across enormous swaths of land (Yong 2012), has revealed the habitat preferences of jaguars and monkeys, and can detect the ecosystem-level effects of invasive understory plants from the air (Asner and Vitousek 2005). Field stations were instrumental in developing the technology—now set to be deployed at NEON sites—by supporting the calibration of airborne measurements to conditions on the ground.

extinctions, and changes in ecosystem composition, structure and function—GEO BON is building scientific consensus on what to measure, and how. The effort could help mobilize global biodiversity research like the Essential Climate Variables did for climate studies

Genomic Tools

In 2001, sequencing a human genome cost about $100,000,000; ten years later it cost $8,000, and the price is still falling (Wetterstrand 2012). The vanishing cost of genetic sequencing creates a host of opportunities. Scientists are discovering life in the sea (Sogin et al. 2006), sequencing an entire ecosystem (see Box 4 on page 8), and assembling the tree of life in detail never before possible. Previously undetectable microbes may now turn out to control key ecosystem processes. DNA in the dirt can reveal which animals, and how many of each, live in an area (Andersen et al. 2012). Methods of capturing genetic diversity in human beings could be extended to guide conservation efforts in key species. A group has proposed a global network of genomic observatories to take the planet's biological pulse (Davies and Field 2012, Davies et al. 2012). Throughout biology, the availability of scalable sequencing tools is opening new doors.

Techniques developed for model organisms in the lab can now be transferred to their close relatives in the wild. Just as fruit flies and mice famously pushed forward discoveries in genetics and medicine, non-model organisms are poised to advance ecology. Combining the powerful toolkits of a model organism approach with realistic and relevant conditions in the field will help elucidate genomic processes in their native ecological context (see Box 11).


Ryan Belnap, NAU IDEA Lab

Box 11. From Genes to Ecosystems

The effects of a single gene can reach an entire ecosystem. A short stretch of cottonwood DNA changes everything from which insects live in the tree canopy, to which stream invertebrates eat the fallen leaves, to how decomposition and nitrogen mineralization work (Whitham et al. 2006). Bringing genomic tools into the wild will help scientists understand, for the first time, the genetic basis of ecosystem processes.

Big Data

It took from the beginning of time until 2003 for humans to create as much digital information as we now generate every two days (Turek 2012). Biology's contribution includes DNA sequences, climate data, taxonomic information, satellite photographs, digitized historical field notes, automated sensing, and more. Data-intensive research provides opportunities to study complex and interconnected systems (NSB 2005, NRC 2009), integrating across research programs to incorporate more interacting factors than a single scientist otherwise could. It is also a tremendous challenge. Data management involves not just cataloging large volumes of the same type of data (e.g., repeated long-term measurements, standardized measurements made on large spatial scales, or sequence data), but also contextualizing and linking different types of data (e.g., field notes, photographs, physiological parameters).

Creating cyberinfrastructure with the ability to discover, integrate, and analyze massive amounts of information is a national priority (PCAST 2010b). The White House has announced a Big Data Research and Development Initiative in recognition of the field's importance to economic growth and prosperity (NEC 2011). The recent launch of DataONE, the Data Observation Network for Earth, overcomes a significant hurdle by enabling access to globally networked environmental data regardless of whether those data were initially collected by the same methods or in the same units or at the same time intervals.

Box 12. Research Platform

Northern Arizona University is building an experimental infrastructure along a gradient that spans a hundred miles. They designed the platform from the start to accommodate multiple, growing, collaborative research projects. The Southwest Experimental Garden Array (SEGA) will use automated sensor networks to control moisture treatments at sites expected to include federal, state, private, and non-profit lands, from a national forest to a ranch to an arboretum. Scientists from many disciplines will use the platform to simulate the effect of climate change on every aspect of the ecosystem.

Experiments as Infrastructure

Historically, a field study was conducted by a single individual. As studies have grown in complexity or taken on value because they have been conducted for extended periods of time, multiple research groups have started to collaborate within the context of a single study (see Box 12). The longest-running warming experiment in the field, begun by John Harte at the Rocky Mountain Biological Laboratory in 1989, has now supported nine doctoral dissertations, five master's theses, and science from plant physiology to evolutionary biology to ecosystem ecology (e.g., Harte and Shaw 1995). Different research groups can apply specialized methods or measurements to the same plots without having to invest in the infrastructure required to run a separate experiment. Additionally, such studies make it easier for scientists to contextualize their work by linking their individual measurements to a broader array of measurements made at the same location.


Charles Curtin

Box 13. Borderlands

Collaboration among stakeholders with different interests but common goals can help scientists ask the right questions. In the Malpai borderlands of southeastern Arizona, ranchers want grass that can support cattle, conservationists want ecosystems that can support grass, and ecologists want to know whether the mice or the cows are controlling the grass. At a time when conservation biology was focusing on single-species problems and single-factor solutions, scientists working with ranchers expanded the vision to multiple interacting factors at the landscape scale (Curtin 2010).

Collaborative Research

As scientists pursue increasingly complex questions, it becomes more important that they work in teams that include a diversity of skill sets and discipline expertise (NRC 2001, NSF BIO/DBI Committee of Visitors Report 2007; see Box 13). The trend across most of science for increasing collaboration is reflected in a steady rise in the number of authors on scientific papers. Additionally, one of the ways that researchers can increase their productivity is to provide a unique contribution to a larger project. Cooperation between academic and resource management institutions can make both academic and management science better (see Box 20 on page 31). Collaborations in environmental science have gradually expanded from within-ecology to within-biology (e.g., adding physiologists) to within-natural science (e.g., adding hydrologists or computational scientists); the trend is now for increasing collaboration between natural and social scientists, from economists to anthropologists to political scientists (see Box 16 on page 25; Palmer 2012).

Science for Sustainability

The point of environmental science is not only to save the planet, but to save its people too. To steward the environment so that it can sustainably support the growing needs of the human population requires science that includes humans as part of the system (see Box 13) and that can inform societal actions. NSF's Science, Engineering, and Education for Sustainability (SEES) program supports this need through widely interdisciplinary research and education activities. Science for sustainability uses social and natural sciences, medicine, engineering, mathematics, and computation, and spans scales from local to global. Place-based research at field stations and marine labs is an important component of this emerging framework, and integrating socio-ecological research into FSMLs is a promising future direction (LTER 2007, 2011).

EDUCATION AND OUTREACH

The scientists at field stations and marine labs study many different aspects of many different ecosystems. What they have in common is a particular rigorous, evidence-based approach to interpreting the world around them and evaluating scientific explanations of it. One of the most important functions of FSMLs is to offer visitors—young scientists, schoolchildren, citizens, college students—a glimpse into the scientist's approach to asking and answering questions. This exposure to science is vital.

Education in science, technology, engineering, and mathematics (STEM) is critical for the nation's future (NRC 2010, Hemingway et al. 2011). It is the engine of scientific discovery and technological innovation and helps maintain the vitality of the economy (NEC 2011). It creates a workforce trained for the future: Science and engineering jobs have grown three times faster over the last ten years than those in other sectors (NEC 2012). Within the sciences, the number of biology jobs is growing steadily (NRC 2003b). Importantly, STEM training prepares citizens to make informed decisions in an increasingly technological, and environmentally challenged, world (Brewer and Smith 2011). FSMLs are nationally recognized as a resource for educational activities, serving as a gateway to the complexity of environmental sciences (Klug et al. 2002).

FSML Contributions to STEM Training and Environmental Outreach

Impact

Exposure to research in the field often inspires students in ways that typical university courses, many of which have dropped the field components of their courses in recent years, may not (Eisner 1982). At a time when the number of science degrees granted (NEC 2011) and interest in science (PCAST 2010a) are falling, FSMLs provide a venue to viscerally engage students in exploration and discovery.

The tight coupling of research and education that is often a hallmark of FSMLs has positive impacts on STEM training (see Box 14; Brownell et al. 2012). Scientists learn how to do science by doing it; and the immersive atmosphere of a field station or marine lab is an ideal training ground. At its heart, an FSML is commonly a community of scholars. Opportunities for mentoring extend far beyond the classroom, especially at a residential facility, and professors are more likely to send a graduate student to a facility that they know has the physical and intellectual resources to support the research.

Box 14. Student Scientists

A new laboratory course that immerses biology majors in ongoing ecological research at Stanford University's Jasper Ridge Biological Preserve teaches students to ask and answer genuine questions, the ones to which no one yet has the answers. In doing original research, the students practice experimental design and techniques and participate in scientific collaboration and communication—and it makes a difference (Kloser et al. 2011). Compared to students in a matched cookbook-lab course, those in the new course had higher self-confidence in lab-related tasks, more positive attitudes towards research, and more interest in pursuing it in the future (Brownell et al. 2012).


Cindy Wilber


Coal Oil Point Reserve

Sixth graders do research with a Stanford student at the Jasper Ridge Biological Preserve (left). A University of California at Santa Barbara graduate student and assistant sample fish at Coal Oil Point Reserve (right).

Perhaps most importantly, undertaking exploration on their own initiative helps students move along the continuum from passive learners to active scientists (NRC 2003b). The opportunity for undergraduates to engage in original research increases both understanding of the scientific process (Lopatto 2007, Brownell et al. 2012) and recruitment of students into science careers (Hunter et al. 2007, Russell et al. 2007). These types of activities can lead to a greater retention of biology majors in the first two years (Jones et al. 2010), which is key to increasing the STEM workforce (PCAST 2012).

Reach

FSMLs play an important role in terms of the number of people they reach. Two-thirds serve K–12 audiences and the general public. Over 90% of FSMLs are involved in undergraduate training, including formal courses, research and service internships, and field trip experiences. Seventy-two percent of FSMLs run undergraduate research internship programs, and more than half indicated an increase in undergraduate enrollment in the previous ten years (Hodder 2009). As a single example, the Organization for Tropical Studies, a consortium of universities and research institutions founded in the early 60s, has enrolled more than 8,000 students of various levels in its courses at three biological field stations in Costa Rica.

In addition to a large number of individual programs, FSMLs are also involved in large-scale educational initiatives. Close to 15% of NSF's Research Experience for Undergraduates (REU) biology programs are hosted through an FSML. Marine labs are the primary host institutions for NSF's Centers for Ocean Sciences Education Excellence (COSEE) programs that have engaged more than 1,300 ocean scientists, 10,000 teachers, and thousands of the general public in ocean science and educational activities over the past decade.

National Priorities

FSMLs are in many ways on the cutting edge of trends in STEM education. Student participation in authentic research, multiple modes of learning, and small student to faculty ratios have been integral to many FSML programs since before such approaches became widely recognized. FSMLs also provide opportunities for collaborative learning, including unique opportunities to integrate research and undergraduate education (Bowne et al. 2011, Kloser et al. 2011). Inquiry-based learning is commonly employed at FSMLs (Hodder 2009).

These approaches reflect national priorities in science education based on directions in both science (NRC 2009) and the science of learning (NRC 2000, 2003b). In the report "Vision and Change in Undergraduate Biology Education" (Brewer and Smith 2011), the American Association for the Advancement of Science (AAAS) emphasized the importance of interdisciplinary communication; of emerging technologies from the molecular to the geospatial; and of large, complex datasets and the computational skills it takes to manage them. Equally important, whether the student will become a biologist or a painter, is that she come away with an understanding of science as a process rather than just a set of facts.

FSMLs are ideally situated to meet these goals. They can and do, as AAAS recommends (Brewer and Smith 2011), "make biology content relevant by presenting problems in a real-life context" and "stimulate the curiosity students have for learning about the natural world." Undergraduates, including those who do not thrive in a formal classroom, get "authentic opportunities to experience the processes, nature, and limits of science."

Increasing the participation in and persistence of underrepresented minorities in STEM fields is another national priority (NRC 2011, PCAST 2010a). FSMLs can help build a future generation of interdisciplinary scientists that reflect the changing face of research in the United States. Underrepresented minorities, like most students, respond positively to the research experiences that FSMLs can provide (Jones et al. 2010); unfortunately, FSMLs are often located far from urban centers and diverse populations. Making the benefits of FSMLs accessible to minorities may require focused efforts.

Outreach

FSMLs provide unique opportunities for increasing environmental literacy, a growing problem in the workforce (Sundberg et al. 2011), among children (Louv 2005), and around the world as a whole (Pyle 2001). In some instances, FSMLs provide the only opportunities students have to take classical courses on organismal biology (Hodder 2009). As our nation grapples with a wide range of environmental challenges, it is critical that we have scientists, employees, decision makers, and a general public that can understand and meaningfully engage with those issues. Many marine labs have been directly involved with the development and dissemination of the Ocean Literacy initiative that has identified seven fundamental principles that increase our understanding of people's impact on the ocean and the ocean's impact on people (Ocean Literacy 2005).

FSMLs are often also embedded in the community in ways that promote public outreach and provide resources and programming for science education from pre-school to lifelong learning. Two-thirds of FSMLs indicate they are involved in K-12 or public programs. While there are many environmental education programs, it is important to note that these programs typically focus on teaching environmental facts. FSMLs are unique in that they provide opportunities for the general public to learn about science as a process and to directly engage with scientists.

STEWARDSHIP: TRANSLATING KNOWLEDGE OF ENVIRONMENTAL PROCESSES INTO IMPROVING LIVES

Environmental science that will make a difference in the face of pervasive human impacts has to take humans into account—our needs and our behaviors as well as our effects (NRC 1999, Kates et al. 2001, Clark 2007, Matson 2009). We need ecosystem research that is relevant to policy decisions (NRC 2004; MA 2005; Carpenter et al. 2006, 2009; IPBES 2012), and conservation that serves not only "pristine" nature but also working landscapes, urban ecosystems, fisheries, forestry, and agriculture (see Box 15; Kareiva et al. 2011b, Marris 2011). We need collaboration, not only among natural scientists but also with social scientists, engineers, business owners, and more (see Box 16; Palmer 2012).

Field stations and marine labs, as a primary resource for understanding the environment, can play an essential role in efforts to achieve a sustainable future for both nature and society. FSMLs allow the integrated study of human and natural processes and of global and local forces. The long-term, place-based data of individual FSMLs inform stewardship at the local level. They provide insight into how global change affects local environmental processes. Their ability to network with other FSMLs creates opportunities to scale up across regions, gradients, and the continent, yielding insights into how local decisions feed back into large-scale processes (Levin and Clark 2010). They are central to the ecological research that enables prediction of biological responses to climate change. They contribute to continental- and global-scale monitoring efforts, and to understanding the services that ecosystems provide. Because they are both embedded in communities and grappling with many of the same issues, such as how to control invasive plants or deal with changing fire regimes, field stations and marine labs create a natural bridge between fundamental science and the decision makers directly confronting challenges on the ground or in the ocean.


Ed Rybczynski

Box 15. Recovery

A few years ago Chesapeake Bay's blue crab fishery was in danger of complete collapse. Today there are more blue crabs in the bay than there have been in almost 20 years. Good science at the Chesapeake Biological Laboratory is partly responsible, but so are good relationships. The policy changes that led to the spectacular recovery depended just as much on the lab's connections with the community, the watermen, and the policy makers as they did on the dredge surveys and mathematical models (T. Miller, pers. comm.).

Box 16. Social Science

Long-term research in the agricultural Yaqui Valley in Mexico has resulted in diagnostic tools that can reduce polluting fertilizer use, saving farmers money without sacrificing yields. But, as an economist who was studying the system found, farmers will not adopt a new technology just because the scientists say it works; they will adopt it after the credit unions say it is a good investment (McCullough and Matson 2011). Social science matters every bit as much as natural science if either is to make an impact in the real world.

To explore how field stations and marine labs can best contribute to a sustainable future, we use the grand challenges framework (Reid et al. 2010) recommended by multiple working groups at the Colorado Springs workshop (NAML and OBFS 2013a).

The Grand Challenges of Global Sustainability

The International Council for Science (ICSU) and the International Social Science Council (ISSC) have proposed a set of grand challenges for global sustainability (Reid et al. 2010). This solution-focused list of the highest priorities for Earth system science addresses the most urgent sustainability problems as defined by society—not just by scientists. We consider the role of field stations and marine labs in each of the ICSU/ISSC's five sustainability grand challenges in turn.

How can FSMLs improve the usefulness of forecasts of environmental conditions and their consequences for people?

No matter how global the change, the consequences people experience are always local. An early spring on the desert floor has different implications than an early spring in the Rocky Mountains. As place-based institutions, FSMLs are in a position to help translate the latest science into locally relevant action. Given regional forecasts of a 2° C rise in air temperature, what can farmers, foresters, or City Hall expect?

The effects of climate change vary across the landscape in ways that current models do not predict. For example, fire behavior will change differently on north-facing than on south-facing slopes. Land managers have to take that into account in their fuel-reduction plans, but the science to support those decisions is not often available. FSMLs have the long-term and contextual data needed to focus climate models on the finer scales useful for management plans.

Increased communication between FSMLs and resource managers would benefit resource managers, but it would also benefit FSMLs. People who use and steward natural resources can drive FSMLs towards providing the knowledge necessary to solve socially relevant problems. FSMLs could actively solicit input from local and regional resource managers, policy makers, educators, and concerned citizens.

How can FSMLs contribute to the development, enhancement, and integration of observation systems to manage global and regional environmental change?

This may be the biggest opportunity for FSMLs to contribute to transformational science. Field stations and marine labs provide a national platform to develop new technology and capacity, including better tools for visualization and minimum data standards for streaming near real-time sensor data. They can identify 'vital signs' and 'sentinels of change' specific to different ecosystem types. They provide platforms for large-scale observing systems like NEON, the OOI, and IOOS; allow beta testing and in situ validation of new generations or types of sensors (see Box 17); and validate and calibrate remotely sensed data. They provide historic baselines for physical (meteorology, stream flow, wave height, etc.), chemical (surface water quality, air quality, contaminants in the environment, etc.), and biological (species composition and diversity, invasive species) variables. Urban LTER sites provide unique opportunities to facilitate place-based research that explicitly incorporates human systems.

How can FSMLs help to determine how to anticipate, avoid, and manage disruptive global environmental change?

Some damage, once done, cannot be repaired. FSMLs are watchtowers for many of the planetary boundaries that, when crossed, could lead to irreversible environmental change (Rockström et al. 2009). FSMLs also support the fundamental research on ecosystem processes that is necessary to predict such tipping points (see Box 18). They enable scientists to forecast ecological conditions, elucidate mechanisms through experimentation, develop and validate models, and document historical levels of natural variability with long-term datasets. Understanding disruptive environmental change is the only way to anticipate, avoid, and manage it.

How can FSMLs help to determine institutional, economic, and behavioral changes to enable effective steps towards global sustainability?

FSMLs are not well equipped to recommend reforms in systems of governance or the values underlying human behavior. However, there are two ways that field research can contribute to changing the global conversation.

First, the effort to value natural capital is crucial to integrating the benefits humans derive from ecosystem functions into both policy and personal choices (NRC 2004, Kareiva et al. 2011a). A logical framework for putting a price on ecosystem services requires an understanding of how the processes that purify water, grow food, regulate climate, etc., are controlled. These data come from FSMLs.

Second, education and outreach have the potential to address the skepticism and disenfranchisement that many segments of the public feel towards science. FSMLs that are embedded in their communities often become trusted sources of information. Opportunities for direct experience of science and of nature demystify environmental science and can bring about the behavioral changes needed to instill greater environmental stewardship.

Box 17. Exhaust

By tracking the amount of atmospheric nitrogen deposited in lakes at different distances from cities, Elser et al. (2009) showed that fossil fuel combustion alters aquatic ecosystems worldwide. The EPA is now gathering data to develop a monitoring network and a future review of secondary emissions standards—in part by installing instrumentation at some of the same field stations that supported the initial sampling.


KOSMOS on Svalbard (Signe Clavsen, GEOMAR)

Box 18. Ocean Acidification

The ocean is getting warmer and more acidic, with potentially abrupt and devastating consequences. But predicting those consequences is extremely tricky: Ecological interactions among hundreds of players from microbes and zooplankton to corals and algae could act to mitigate or to amplify the change, through their effects on each other or on ocean chemistry. To integrate across all of those factors, scientists do experiments in the ocean itself. Using mesocosms—enclosures that isolate a representative subset of a specific ecosystem and allow it to be manipulated—can help predict the sum total response of the ecosystem, and the fate of the seas (Nejstgaard 2010).

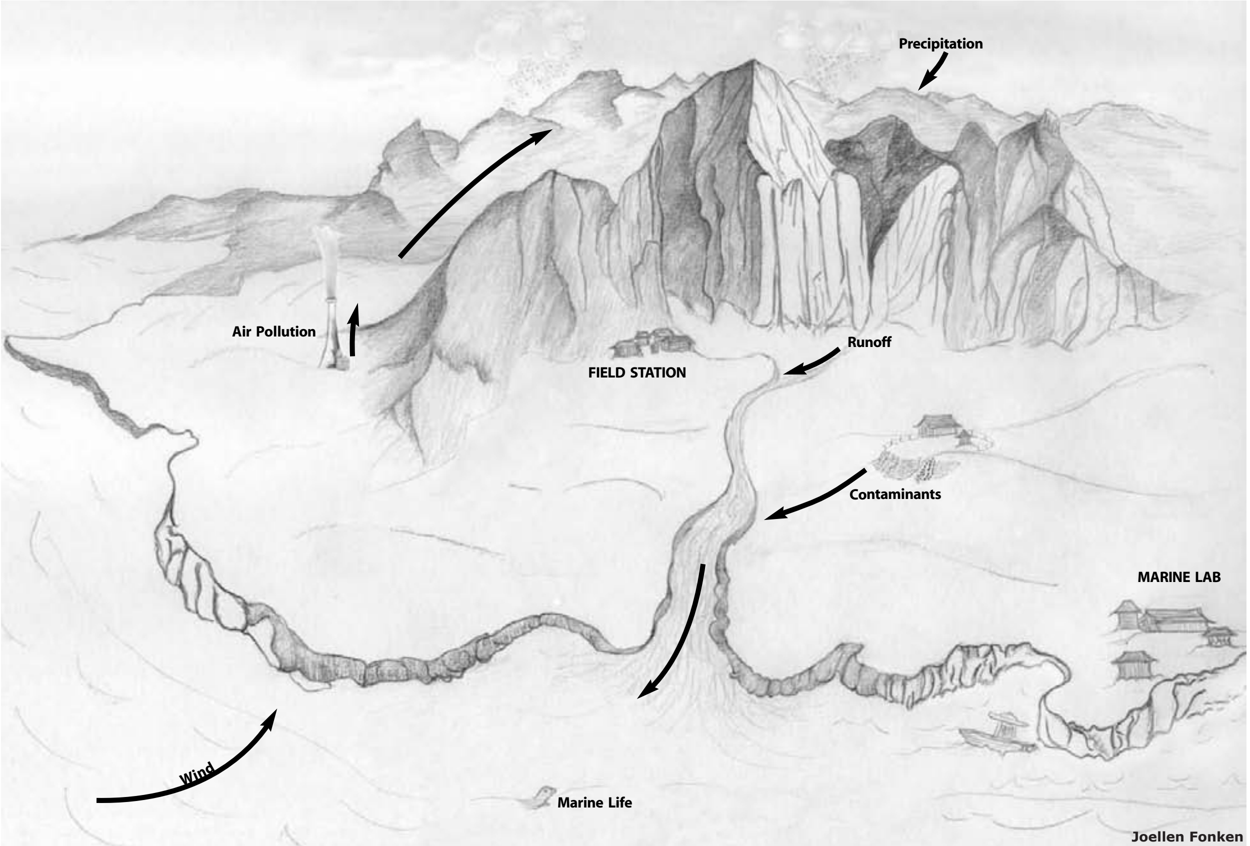
How can FSMLs encourage innovation in technological, policy, and social responses to achieve global sustainability?

To encourage social innovation, FSMLs could begin to scale the type of data they collect to encompass human components as an integral part of natural systems. This will require the incorporation of social sciences into research programs (Palmer 2012). For example, the collection of human use data from the coastal zone is a critical element in coastal and marine spatial planning.

The FSML setting is conducive to such multidisciplinary collaboration. Socio-environmental research programs that include social and natural scientists at every phase of the project—starting with framing the question—mesh well with the culture and history of FSMLs.

THE FUTURE OF FSMLS

Standing at the intersection of science and nature, field stations and marine labs are playing an increasingly important role in providing the knowledge needed to address environmental challenges. A tradition of wide-ranging terrestrial, aquatic, and marine research has endowed FSMLs with rich datasets that encompass many aspects of the natural world and the changes that have occurred over the past century. Their broad spatial distribution provides opportunities for scientists to work across a staggering range of spatial scales, from single meter plots to continents. Furthermore, they serve as the nexus for the interdisciplinary collaborations needed to weave multiple strands of knowledge together to address complex problems. As place-based facilities, field stations and marine labs are also the gateways to nature and windows to the sea that allow learners of all ages to connect with and better understand the challenges facing the environment. The future of FSMLs will take advantage of these strengths.



Joellen Fonken

Figure 3. Landscapes to seascapes: Terrestrial, aquatic, and marine processes are interconnected, and field stations and marine labs can work together to promote a fuller understanding of our complex environment.

A critical part of the future of FSMLs will be ensuring that the data collected by individual researchers and FSMLs will be accessible to scientists from around the nation and world. Not only historical data but also torrents of new data, whether from automated sensors or human observations, will flow freely among sites and into coordinated data management systems with visualization tools that promote insight across scales of space, time, and biological organization. A vibrant, interconnected series of multi-investigator, multi-site national research programs will utilize the full breadth of FSMLs and enable scientists to cross traditional disciplinary and geographical boundaries. Modern cyberinfrastructure, including telecommunications and the database infrastructures needed to support the data streams, will ensure that FSMLs continue to serve as a foundation for national initiatives such as the National Ecological Observatory Network (NEON), the Ocean Observatories Initiative (OOI), the Integrated Ocean Observing System (IOOS), and the Long-Term Ecological Research (LTER) network.

Enhanced networking opportunities will help accelerate scientific progress. FSMLs will develop a coordinated framework that facilitates integrated research linking the components of ecological interactions from the mountains to the sea (see Figure 3). The Organization of Biological Field Stations (OBFS) and the National Association of Marine Labs (NAML) will regularly hold joint meetings, and establish strong working relationships with other key FSML stakeholders including observing networks, state and national agencies, land trusts, and scientific societies. These relationships will foster a dynamic interplay between policy makers, natural resource managers, and researchers that advances solutions for a sustainable future. Generations of scientists and students trained in the vibrant intellectual community of an FSML will use their on-the-ground scientific experience to address issues in environmental biology and beyond. Wide-ranging, transdisciplinary natural and social sciences research activities fully based in the local environment will create diverse outreach and formal and informal education opportunities. The FSMLs of the future will unite their disparate strengths to catalyze innovation, education, and environmental stewardship.

Key Investments for the Future of FSMLs

The goal of this report is to help achieve the vision described above. We have identified critical emerging issues in environmental science, education, and stewardship, and distilled from these the scientific trends to which FSMLs can best contribute. We now consider the infrastructure components, and the management and operations practices, that would most enhance FSMLs' contributions to science and society. Which investments in FSMLs will yield the greatest returns for research, education, and stewardship?

Access

The accumulation of place-based knowledge that defines the value of field stations and marine labs depends on reliable access to research sites. Sites directly controlled by FSMLs are often ideal; FSMLs can provide security and ensure long-term access. Additionally, studies that involve ground disturbance or permanent installations may trigger environmental review processes if conducted on public lands, so working on privately owned land may considerably reduce the costs of research.

But neither the environment nor the environmental science stops at the fence. Society's pressing questions increasingly require research at

Box 19. Connectivity

After shrimpers in the Gulf of Mexico started running into "dead zones" without any shrimp, scientists at the Louisiana Universities Marine Consortium connected the problem to low levels of oxygen in the water. They found that the cause stretches all the way up the Mississippi River, where nutrients—from fertilizers applied to corn and other crops as well as from ranches, urban wastewater, industrial discharges, and air pollution—collect in the river and eventually run into the Gulf. Research on the issue encompasses the entire watershed and the people who use both the land and the sea, and has led to federal legislation to combat oxygen depletion in the Gulf of Mexico and beyond (Nuwer 2012).

larger scales (see Box 19). FSMLs need to consider the landscape and region in which they are embedded: Who owns and manages the land, and how can the FSML best collaborate with them?

Historically, public lands and marine areas have been an important part of the nation's scientific portfolio for environmental science. However, access to public lands is becoming increasingly problematic. For example, one of the original motivating factors for the establishment of wilderness was to provide an opportunity to have untrammeled areas to place environmental change within a larger perspective. The reality, however, is that wilderness areas are often being managed almost solely for recreation. Limitations are placed on science even when those limitations are meaningless within the context of recreational impacts. Additionally, the increasing complexity of National Environmental Policy Act (NEPA) compliance is either stopping research, or increasing its costs on any public lands. Finally, many federal agencies face increasing pressures on public lands at the same time they are experiencing a significant decline in management resources. When those agencies see no direct benefit to the research—and they are often staffed by people with expertise sets outside the sciences—the common response is to delay or prohibit research. In some instances, the agencies can even be outright hostile (Parsons 2004). If these issues are not resolved, they will fundamentally undercut the ability of the nation to generate the science it needs. There is a compelling need to **develop a strategy for supporting research on public lands** (Pringle and Collins 2004) and facilitating productive research-management partnerships (see Box 20).

Collaboration and Complexity

While logistical support for researchers in the field is still a critical part of what FSMLs do, the value for science has shifted away from being defined largely by logistical considerations to being defined largely by the richness of what is known about a site. Insight into complex environmental processes comes from the accumulation of knowledge about a particular place, combined with productive interactions

Box 20. Collaboration

At H.J. Andrews Experimental Forest, a long-standing federal-academic partnership has produced strong scientific outcomes that matter to policy and make a difference to the environment. Oregon State University and the US Forest Service (USFS) research branch share facilities and have joint control over research decisions. The local USFS lands branch—which houses the nation's only scientific liaison—facilitates the NEPA process, among other responsibilities in the research-management partnership. Because the land managers in charge of complying with NEPA regulations are familiar with research practices and potential impacts, which may differ from those of more typical uses, the process goes smoothly and takes no more than a few months for larger projects. The collaboration between scientists and managers has resulted in research that helped ecosystem-based management take off in the Pacific Northwest and has shaped new federal land management policies related to old-growth forests, streams, and biodiversity (Driscoll et al. 2012).

between the individuals who accumulate it. Consequently, one of the main recommendations we offer in this report is to **increase opportunities for scientists to collaborate and to integrate the diversity of place-based discoveries in interesting and meaningful ways.**

When collaboration extends across institutional boundaries, the benefits increase (Swanson et al. 2010). In particular, academics and resource managers together have the potential to enhance stewardship much more than either alone (see Box 20; Driscoll et al. 2012). Sharing resources can also greatly increase efficiencies. For example, while the ecological community in the United States has invested comparatively little in critical aquatic mesocosm infrastructure, tanks they could be using to test hypotheses about ocean acidification are sitting open at Agricultural Experiment Stations' aquaculture facilities.

Looking Back in Time

A critical task confronting FSMLs is to deal with historic and endangered data (Brunt and Michener 2009), a general issue for science (Nordling 2010). One of the unique contributions FSMLs provide is the ability to look backward in time. Not only do historic data provide insights into how the world is changing, but they also provide an essential baseline for interpreting future observations (see Box 21). The high rate of environmental change means that the most stable ecosystems we will ever see are past ecosystems.

While there are numerous attempts underway to manage and capture data associated with contemporary studies, including the requirements of journals and funders to publish data/metadata, those efforts have little impact on historic data. Until a concerted effort is made to **identify and archive historic datasets**, our ability to look backwards in time will steadily degrade (Strayer et al. 1986).

Big Data

Field science is making rapid progress as scientists develop tools that measure new parameters in the field, or that reduce the cost of measuring. Two areas of current growth involve automated sensors and genetic tools. The need to upgrade our data management systems to better capture such data streams is a priority.


Brian Helmuth

Box 21. The Past for the Future

Long-term and historical data from FSMLs are critical to forecasting the biological consequences of climate change. At marine labs from southern California to northern Washington, data loggers inside black epoxy "robomussels" recorded temperatures for several years in a row to measure real mussels' heat stress. They showed that small-scale, local factors can overwhelm regional gradients: Mussels in the cold north get hotter than those in the south, because their temperature depends on the timing of the tides more than the weather (Gilman et al. 2006, Helmuth et al. 2002). Historical records of tidal cycles at several marine labs, in combination with forecasts of future conditions, helped the researchers make temporally specific, biologically informed, and site-specific predictions of mussels' fate in a changing climate.

In terms of data management, particular attention will need to be paid to data captured by people rather than sensors (Robbins 2011). Human-collected data is more challenging to aggregate because it adapts to the idiosyncratic needs of each particular situation. Unlike sensors, the amount of metadata needed to describe it is high relative to the volume of information. And almost by definition, the process cannot be automated to reduce the time involved. While 95% of scientists in evolution and ecology believe such data should be publicly managed (Whitlock et al. 2010), the scientists collecting it typically have little incentive to participate in publicly accessible data management systems (Robbins 2011). **Real progress on data capture will be made when scientists have positive incentives to participate** (Porter and Callahan 1994). Providing scientists with tools that increase their data management efficiency and that allow them to embed their individual studies within the context of other data streams—and capturing data/metadata as a consequence of those tools—will substantially increase our ability to manage human-captured data.

Harnessing the richness of the data streams emerging from FSMLs will be a challenge. While there is no analogue for Moore's Law for computing power, there is little doubt that the amount of data available to scientists from FSMLs will increase rapidly in the future (Robbins 2011). As the cost of data collection and management continues to drop, the focus will turn to the ability to use the information, both in terms of access to the data as well as integration (NSF DEB Committee of Visitors 2006). A whole new range of data visualization tools will need to be developed (Gray 2007, Porter et al. 2012).

One Experiment, Many Investigators

An exciting area of growth at FSMLs is the development of long-term, large-scale studies as platforms for multiple research groups (Janzen 2009, Lindenmayer and Likens 2009). As scientists collaborate and work on larger spatial and temporal scales, the way we think about long-term research projects will evolve. Experimental manipulations in the field take an extraordinary amount of effort to implement, but for any single perturbation—such as warming a mountaintop—many different research questions can be asked.

Historically, most field manipulations have been designed around the needs of a single scientist. Such studies are inherently limited in scale because there is only so much that a single scientist can manage. Also, these studies are limited in value because they are not designed with an eye to expansion or to use by other groups. **Field studies managed as infrastructure projects by an institution hold great promise.** There is a history of such studies, including the Biological Dynamics of Forest Fragments Project, the LTER network, and more recently, Northern Arizona University's Southwest Experimental Garden Array (see Box 12 on page 20). Advanced European mesocosm facilities, such as the German-developed KOSMOS system (http://mesoaqua.eu/kiel_kosmos) and large-scale LakeLab (http://www.seelabor.de), are successfully supporting dozens of simultaneous investigators.

Networking

At the largest scales, such complicated field studies will involve networks of field stations such as the replicated, standardized experiments advocated recently by Knapp et al. (2012) or the successful international grassroots collaboration of the Global Lake Ecological Observatory Network (GLEON). Networking of FSMLs will continue a trend already seen with the LTER, NEON, OOI, and IOOS programs. Ultimately these networking activities will push FSMLs in new directions. For example, while historically field stations have participated in OBFS to share information on how to operate individual FSMLs effectively, FSMLs are increasingly participating in networks because it expands the type of science that they can support. OBFS and NAML will need to adapt and play a greater role in networking to **facilitate science on broader scales** (Lohr et al. 1995, OBFS 1999).

It is important to note that these types of complicated, large-scale, networked studies will not replace site-specific, often small-scale studies, but rather complement them. In the survey, the most often cited impediment to cross-site research was not data management (46%) or administrative hurdles (19%), but a lack of interest in cross-site questions (64%). Field science often involves a degree of innovation that requires site-specific approaches and designs that do not lend themselves to standardized protocols across widely varying landscapes (see Box 22). Consequently, efforts to coordinate the work of individual scientists must recognize both the need for innovation—which requires new and unique approaches to observing the world—and the incentive-structure within which those scientists work.

Box 22. Standardization vs. Flexibility

The state of Colorado monitors water quality using a standard protocol that reliably detects nutrient loading across the state. But water quality can suffer from problems other than nutrient loading. Some communities—for example, in areas that have been extensively mined—are more likely to be contaminated by heavy metals than by nitrogen or phosphorus. A protocol designed to use stream insects as bioindicators for nutrient loading will fail to detect heavy metal contamination, because different stream insects respond to different water quality issues (B. Peckarsky, pers. comm.). While standardized measurements like Colorado's provide power to assess large-scale patterns, they also restrict the set of locally relevant questions you can ask.

Long-Term Monitoring

Interestingly, while long-term monitoring emerged as the sixth most commonly cited critical infrastructure component in the survey of FSMLs (NAML and OBFS 2013b), it was also considered one of the infrastructure components most in need of investment. Field stations and marine labs currently maintain many records specific to their locations, including weather data, biological collections, water quality, flowering phenology, fire histories, and paleoecological data. Many have been monitoring local populations for decades, keeping track of the salamanders, the scrub jays, or every tree in the forest. **Handling long-term monitoring**, which could include operating sensor networks or managing more complex field studies as described above, **is perhaps one of the most scientifically valuable functions FSMLs can provide**. It is also one of the most difficult activities for FSMLs to handle on a sustainable basis. Indeed, maintaining the infrastructure for long-term projects can be particularly challenging when funders often prefer to support new initiatives (ESA 2011).

Organizational Capacity

Finally, as we look to the future, we consider it important to note that the growing complexity of field research will put considerable stress on FSML operations. Supporting new types of science requires greater institutional capacity for a wide range of functions, including managing sensors, archiving historic data, managing data streams, and supporting new types of equipment. With an increasing focus on complex, collaborative projects, more project management skills are needed, as are the people skills to coordinate multiple research groups. Participating in networking requires time.

These challenges are heightened by the organizational structure of many FSMLs. Three quarters of FSMLs are operated under the umbrella of a single university or college, with considerable institutional funds devoted to those operations. On the other hand, FSMLs work best when they host a wide range of scientists, regardless of the institutional affiliations of those scientists. These types of environments allow for collaboration and synergies. Larger institutions often explicitly encourage this type of use; they have sufficient staff to absorb the needs of visiting scientists at little additional cost, and they have financial systems that can aid with cost recovery as needed. However, smaller institutions may be pressed to host visiting scientists without creating a sense that the host institution is subsidizing other schools.

FSMLs organized as not-for-profits face a related, though different, challenge. They are often highly successful precisely because they are designed to serve multiple research institutions. However, in the absence of a host institution, it can be extremely difficult for such a facility to become large enough to be financially viable. When it works, it works very well. But it can be hard to get started.

For FSMLs to thrive in the future, it will be important for them to develop the organizational capacity to meet management challenges, which includes maintaining the financial viability of the FSML in increasingly difficult economic environments. Our recommendations for increasing the management capacity of FSMLs do not involve a one-size-fits-all vision of what an FSML can do, but are meant to nurture FSMLs through all of their stages of institutional development.

Below we propose five overarching goals related to maximizing the unique contributions of FSMLs to science and society, and a set of potential actions to help achieve them.

Recommendations: Goals and Actions

The Steering Committee has developed a set of recommended goals and actions to help maximize the unique value of field stations and marine labs. The recommendations stem from a range of considerations including emerging scientific trends; observations on how FSMLs might be made more effective, both individually and as a network; and an evaluation of the key investments that would have the biggest impact on emerging scientific trends, as outlined above. These recommendations are directed to a diversity of audiences, including OBFS, NAML, and similar organizational networks; individual FSMLs and decision makers within those FSMLs; and relevant policy makers and funders. The following goals and potential actions are not meant to be prescriptive, but rather a starting point for consideration. While not in strict order of priority, the actions we consider more critical are listed higher up and in boldface.

Goal 1: Increase the value to society of the science done at FMSLs, as well as the public understanding of that value.

FSMLs are one of the world's primary assets for understanding the environment in a period of dramatic and far-reaching environmental change. Given the wide range of challenges that humans face—from climate change, to the accelerating loss of biodiversity, to invasive organisms, to increasing population numbers—it is vital that the full societal value of investments in field research be realized. It is also important, in order for those investments to continue, that the public understand and appreciate those achievements.

Scientists do not always do the research that decision makers need, and decision makers do not always use the research that scientists do. FSMLs are in a position to help bridge that gap. They have a tradition of promoting collaborative research and action, and as institutions embedded in local communities that face their own resource management issues, they have unique opportunities to engage with society.

Recommended Actions:

1. Seek ways to accelerate the process by which fundamental research is translated into societal benefit. Identify the factors that allow good science to guide policy decisions, either through assessment or by building a logic model taking advantage of existing case studies. Following the NRC's (2001) Grand Challenges report and Carpenter et al. (2009), **establish a stronger link between science at field stations and societal benef**it.
2. **Increase the flow of information between scientists and decision makers**, and between academic and agency scientists. As an initial step, FSMLs should reach out to the local offices of federal resource management agencies such as the National Marine Fisheries Service, National Marine Sanctuaries, National Park Service, U.S. Fish and Wildlife Service, U.S. Forest Service, and Bureau of Land Management, as well as to state agencies (Departments of Fish and Wildlife, Environmental Protection) and land trusts to foster dialogue. NOAA's National Sea Grant College Program and the Department of the Interior's Landscape Conservation Cooperatives are models of collaboration between science and management.
3. Build mechanisms into OBFS and NAML meetings to highlight research success stories, and provide training sessions for members on this topic. Develop an avenue within OBFS and NAML to document and **share the successes of FSML research with journalists, educators, and the public.**

Goal 2: Increase the scientific value of FSMLs by increasing the flow of information, both between FSMLs and scientists and among FSMLs themselves.

Objective A: Develop a more comprehensive network of FSMLs.

Scientific discovery, education, and environmental stewardship all rely on communication and collaboration—between scientists, with the public, among individual FSMLs, and between the network of FSMLs and other networks. Leveraging the existing investment in field stations and marine labs means sharing information, access, and resources among institutions with common goals.

The web of potential partners extends worldwide. Many of the world's most vexing environmental challenges, such as climate change and invasive species, have a truly global dimension that will best be addressed with an international response. More effective, comprehensive global networks of FSMLs will be needed to provide the temporal and spatial scale of response necessary to fully understand these complex issues. OBFS has international members in its organization, and NAML is a founding member of the World Association of Marine Stations (WAMS). WAMS was approved as an organization of the Assembly of the UNESCO-Intergovernmental Oceanographic Commission on April 14, 2010.

Recommended Actions:

1. **Establish a Network Center** to provide the resources, expertise, and continuity needed to maximize the value of place-based research institutions. The Network Center would facilitate many of the recommendations put forward in this report, including sharing information among FSMLs for operational, scientific, and educational support; increasing collaboration among scientists at different research stations; managing data; communicating with the public; and coordinating outreach to related research networks. This national Center, tentatively titled "Terramar," would also serve as an organizing unit to further international efforts.
2. Working through the Network Center, **ensure that place-based research institutions are included in national and international strategic initiatives for the environmental sciences**. For example, the Network Center could help FSMLs present their diverse assets to coordinating bodies such as the National Climate Assessment's NCAnet and the Office of Science and Technology Policy's Roundtable on Climate Information and Services.
3. **Create a stronger integration between field stations and marine labs,** including but not limited to hosting a joint meeting between OBFS and NAML in 2014 as well as promoting and encouraging opportunities for joint research at the land-sea interface.
4. Step up membership drive efforts to increase the number of FSMLs represented in NAML and OBFS. **Focus on supporting any institution hosting sustained research in a geographically defined area, and avoid definitions tied to constructs unrelated to the science** (e.g., the presence of housing or laboratories).
5. Develop a searchable online database of FSMLs and their activities, including location, accessible habitats, research foci, and available data.
6. Reach out to organizations already serving networks of field-based research institutions, such as the National Park Service, the USFS Experimental Forests and Ranges, the National Estuarine Research Reserve System, state Agricultural Experiment Stations, and the LTER network (following the LTER Strategic Plan 2011).
7. Move towards collecting data, particularly sensor data, in standardized formats that allow for easy aggregation across FSMLs. DataONE provides tools for data management planning and best practices.

Objective B: Increase the ability of scientists to take advantage of FSMLs.

An individual FSML offers an incredible variety and diversity of resources for individual scientists. Given that those opportunities are spread over more than 500 institutions, it can be difficult for scientists to find the exact combination of resources they need. Additionally, the lack of organized information about FSMLs makes it difficult to think creatively about how work at individual FSMLs might be coordinated to facilitate research on larger spatial scales. Furthermore, efforts to provide efficient access to information, including data, across FSMLs must focus on the unique scientific value of FSMLs. Because the power of FSMLs often lies in their flexibility and their ability to embrace complexity—including opportunities to contextualize data, to validate large-scale patterns, and to test and refine hypotheses—our attempts to organize information should focus not just on capturing data and standardizing protocols (where appropriate), but on capturing the rich diversity of data and resources available at individual sites. While data management is becoming important to providing scientific value, only 10% of FSMLs indicated in the survey that their data management systems were in excellent condition and more than 20% indicated the systems were less than functional.

Recommended Actions:

1. Broaden national efforts to **improve data management for field-based studies** (following Brunt and Michener 2009) to include the wide range of information that provides context, including historical records, photographs, and journals. To take advantage of the unique scientific potential of FSMLs, efforts to capture and communicate the resources at individual FSMLs must **embrace their richness and complexity rather than focus entirely on standardized data streams.**
2. **Develop site-specific data catalogs** to facilitate a stronger flow of information about the scientific potential of FSMLs to scientists. Species lists, maps, weather, and land use history can make a big difference to the design of an experiment, and the survey indicated that these were commonly lacking at FSMLs.
3. Increase data-sharing by FSMLs and investigators by reducing the cost of, and providing incentives for, participation.
4. Support the archiving of valuable historic datasets.
5. FSMLs should consider providing more opportunities for training in informatics, particularly in techniques that take advantage of the rich and complex data streams emerging from FSMLs.
6. Maintain sufficient bandwidth (defined on a case-by-case basis) to accommodate the flow of information to, within, and from FSMLs.
7. When appropriate, colleges and universities should consider managing FSMLs at an administrative level that encourages cross-disciplinary use.
8. Identify mechanisms to improve tracking of the number of scientists, including NSF-funded scientists, whose work depends critically upon FSMLs. This should include both scientists conducting fieldwork at FSMLs and scientists using data generated at FSMLs.
9. Engage with professional societies to increase their awareness of FSMLs.
10. Facilitate sharing information on the opportunities available at FSMLs.

Goal 3: Enhance the synergies between research and education.

Given the large number of FSMLs that cite secondary education as a core part of their operations (NAML and OBFS 2013b), it is clear that many students are receiving significant STEM training at FSMLs. Anecdotal observations of lives transformed and stories told by students suggests that time at FSMLs can have life-long impacts on students. Many scientists cite a field station or marine lab experience as being the one that led them to adopt science as a vocation. Students who do not go on in the sciences have also described their time at an FSML as providing an important understanding of how science is conducted. One challenge, which is not unique to FSMLs, is attracting students who represent the nation's diversity. Partnerships between FSMLs and urban institutions have had some success in increasing underrepresented minority participation, but much more needs to be done to ensure that students from diverse backgrounds have opportunities for a field experience.

Our recommendations for STEM training at FSMLs are focused on more deeply understanding whether, and how, FSMLs are successful at education. Indeed, given the diversity of STEM approaches being implemented at FSMLs, we believe there are unique opportunities to better understand how to provide STEM training.

Recommended Actions:

1. Conduct an assessment of the impact that field stations and marine labs have on STEM training. **Are FSMLs unusually effective at STEM training for at least some students, and if so, why?**
2. **Determine the critical factors for successful STEM training at FSMLs.**
3. Assess which student populations are most likely to benefit from STEM training.
4. **Increase human diversity at FSMLs.** There is no one way to accomplish this goal; a variety of actions will be needed to ensure that the FSML community begins to move towards reflecting the nation's diversity.
5. Provide more opportunities for successful programs to spread.
6. Explore how social media can be used to engage and recruit new audiences to FSMLs.
7. Use cyberlearning as an opportunity to expand the education impacts of FSMLs (e.g., NSF Taskforce on Cyberlearning 2008).

Goal 4: Promote the flow of scientific information for environmental stewardship by ensuring appropriate access by scientists and students to terrestrial, aquatic, and marine systems.

The future of environmental science depends on access to the environment. To do the best possible research on critical environmental issues, scientists need to study increasingly large areas and they need to be able to conduct manipulative experiments. Both aspects present challenges.

Landscape-scale studies require coordination across a diversity of landowners, agendas, and perspectives. For example, while some field stations depend on access to the surrounding public lands, the land managers who control that access vary greatly in the priority they put on science. Important decades-long studies can be jeopardized by simple staff turnover at a federal agency.

At the same time, the kind of manipulation-intensive science that public land managers need to guide their management decisions is often much easier to conduct on private land. Because field stations operate under fewer regulatory constraints, they are able test alternative stewardship scenarios and help drive environmental decision-making. As large-scale living laboratories that make research on different management options tractable, field stations could be a valuable resource for local land managers.

Recommended Actions:

1. OBFS and NAML should initiate discussions at the highest levels of relevant public agencies to **develop a national strategy to ensure access for scientists and students to public areas**, including lands managed by the US Forest Service and the Bureau of Land Management as well as marine reserves. This strategy could include making it easier for FSMLs to obtain special use permits, as well as establishing scientific research and education as important management components of public land.
2. When appropriate, FSMLs should **facilitate research on larger spatial scales**, either by increasing their own land holdings or collaborating with private landowners, non-profits, land trusts, or public agencies.
3. Field stations, with a land base dedicated to scientific research, can **provide opportunities for land use manipulations** and alternative land management regimes in terrestrial ecosystems—such as hydrological, fire, or grazing regimes—that will facilitate experimental and long-term observational approaches by the scientific and resource management communities. FSMLs with this capacity should consider joining and/or forming regional and continent-wide networks that can address responses to such manipulations at broader spatial and temporal scales.

Goal 5: Increase the operational effectiveness of FSMLs.

Objective A: Enhance the effectiveness of individuals working at FSMLs.

Operation of an FSML can involve a wide range of skill sets, including managing a physical plant, fundraising, land management, finances, marketing, and personnel management. These skills are fundamental to a successful operation. For example, while understanding an FSML's finances enables long-term planning as well as facilitates use by outside groups (ESA 2011), many FSMLs lack a transparent cost structure. Many FSMLs are managed by people who received completely different training—often as scientists. But there are commonalities to operating FSMLs. Given the significant existing investment in FSMLs, as well as the trend towards using larger research teams to solve complex problems, we recommend developing training opportunities to integrate the programmatic needs of FSMLs with modern management training. In the survey, investing in training opportunities for management was one of the most cited recommendations for an investment likely to yield the greatest return. Related to that, the ability to "market" an FSML, or articulate the value of an FSML to relevant stakeholders such as administrators, funders, and private donors, was also considered essential. Providing FSML managers/directors with effective tools for communicating the importance of FSMLs could help maintain the support of the administration at the host institution—which was identified as the most critical factor for maintaining the long-term sustainability of FSMLs—and procure donations, which were more likely to be cited as a critical funding source than fees.

Recommended Actions:

1. Develop mechanisms to **provide management and leadership training** for the diversity of FSMLs.
2. Develop mechanisms to provide training to manage large-scale integrative science projects.
3. Enhance the ability of institutions to manage assets by advertising and/or increasing training opportunities as needed.

Objective B: Maintain and improve critical infrastructure.

FSMLs typically involve significant physical infrastructure. Much of this infrastructure does not include elements that are directly related to science, such as housing, dining halls, waste water systems, and telecommunications. However, just as we would never send an astronaut to the moon, or a scientist to explore the deep sea, without provisions to live, sleep, and eat, FSMLs must provide the full range of services needed to support scientists in the field (NSF BIO/DBI Committee of Visitors Report 2007). Furthermore, there is a growing appreciation that the architectural and social contexts of a scientific institution can have a significant impact on scientific productivity (Lehrer 2012, Gertner 2012). A well-designed dining hall can support innovation. Given that one of the valuable features of a research station is the highly interactive and collaborative environment, FSMLs should be attentive to the design of their shared spaces as well as of their research labs.

The needs of any individual FSML are highly dependent upon its specific circumstances and the nature of the programs it is supporting. Consequently there is no set of recommendations concerning physical infrastructure that fits all, or even most, FSMLs. However, we do summarize some recommendations that individual FSMLs should consider, based on emerging trends in the sciences and the unique roles that FSMLs play within science in general. For planning purposes we identify the critical infrastructure elements that FSMLs struggle with most often.

Recommended Actions:

1. When appropriate, FSMLs should provide facilities that **support informal and serendipitous exchanges of information.**
2. Given the increase in the deployment of sensors and the desire for access to real-time data, FSMLs should carefully **plan for significant bandwidth requirements**. Internet access is one of the elements most in need of investment according to the survey, and as mentioned in Goal 2, it increases the ability of scientists to take advantage of FSMLs.
3. FSMLs should be careful to provide only the facilities they need to successfully serve as a bridge between the environment and laboratory facilities on a main campus; they should **avoid unnecessary duplication of facilities.** While research laboratory space is commonly cited as a critical infrastructure component, 20% of FSMLs rate their space as less than functional.
4. FSMLs should consider providing appropriate facilities for the collection of biosamples, such as an ultra cold freezer or liquid nitrogen for scientists working on RNA and other degradable molecules, as well as maintaining traditional collections, e.g., an herbarium, to facilitate access to relevant natural history information. More than 20% of FSMLs indicate that they struggle with refrigeration/freezer capacity.
5. FSMLs should consider maintaining a geodatabase, even if it is crude, to facilitate the contextualization of individual scientific projects, and to make it easier to tie observations together geographically.
6. Storage was rated as one of the critical facilities most in need of investment, with 30% of FSMLs indicating that storage is less than functional.
7. In keeping with the environmental goals of field stations and marine labs, the construction of new facilities should demonstrate principles of sustainability and energy efficiency. The U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) certification program provides a framework for green building design; the Labs21 program and the International Institute for Sustainable Laboratories offer resources specific to high-performance laboratories.

CONCLUSIONS AND FUTURE DIRECTIONS

While it may not be the greatest time to be a human being, it is an exciting time to be a field biologist (Kolbert 2006). Given the ever-increasing range and rate of environmental challenges and change that we face, it has never been more important to understand the environment; never has the world required so much of field scientists and the institutions that support them.

Meeting the environmental challenges will require a fundamental understanding of how the world works. To predict and manage environmental change, we will need to layer our understanding of important processes onto a baseline of how those processes have worked in the past. This requires the integration of historic data and current monitoring systems. Furthermore, we need the ability to understand processes occurring on all scales, from local to global, including the feedback loops among those different scales. Consequently we need not only the ability to understand a single location in depth, but the ability to integrate streams of information from places around the globe. Translating fundamental knowledge into practical applications will require a rich dialogue between scientists and decision makers, a dialogue that will benefit both the science and the decision-making. And because environmental processes are now fundamentally entwined with human systems, field science will need to be integrated with the social sciences and embedded in local communities and the larger society. In short, if a network of field stations and marine labs did not exist, we would have to invent and invest in one in short order.

The FSML network can be thought of as a series of telescopes distributed across the world and focused on the environment. Some FSMLs are located in exotic locations, such as Pacific Islands, mountaintops, or stunning coasts. Others are located in urban areas, next to large cities, or next to farms. All of them serve as portals to the natural world. As a spatially distributed network they create capacity to observe a rich diversity of locations in great depth, as well as the ability to integrate observations from around the planet.

As a highly flexible network, they provide the opportunity for scientists to adaptively and flexibly pursue important questions as they emerge. While automated and standardized data collection facilitates the detection of long-term or large-scale patterns, testing hypotheses that allow insight into the processes that create those patterns requires the ability to explore other existing long-term data streams, initiate new data streams, or manipulate the environment. The value of large-scale, networked data streams is greatly enriched by the ability to use FSMLs to conduct additional analyses or experiments to explain the patterns they detect.

FSMLs have a history of strong scientific productivity, a pattern that will continue. We have identified ten scientific trends involving a range of subjects—including long-term studies, broader spatial scales, biodiversity, ecological genomics, sophisticated ways to generate and manage new data streams, and prediction and stewardship of the future—that rely heavily upon FSMLs. FSMLs form a critical foundation for important scientific initiatives, including LTER, NEON, and IOOS.

As a challenging economic environment limits future spending on science, the existing investment in FSMLs should not be undervalued. We estimate that there is a standing investment by multiple federal and state agencies, private and public colleges/universities, nonprofits, and private donors in

FSMLs worth billions of dollars. This investment includes the value of the land, the buildings, and the equipment, much of which is highly specialized. Perhaps more important, though harder to quantify, are the intangibles. FSMLs maintain priceless long-term information; staff with extensive technical expertise on facilitating science in the field; the systems needed to ensure the integrity of monitoring systems; site-specific knowledge accumulated by tens of thousands of field biologists across generations; world-class educational experiences and facilities and relationships within local communities that ensure continuing access to research sites and that foster dialogues with policy makers, resource managers, and the public in general.

An additional advantage of the highly distributed nature of FSMLs is that their financial plans are inherently diversified. While any one FSML may face a financial challenge, as a research portfolio they sit on a broad foundation of funding that streams in from host institutions, foundations, private funders, and federal and state agencies. At a time when scientific infrastructure needs are expanding faster than our ability to fund operations and maintenance (ESA 2011), this diversification strengthens the FSML network. It also supports further investments in national priorities such as the LTER program, NEON, the maintenance of databases (NSF BIO/DBI Committee of Visitors Report 2007), and the Research Experience for Undergraduates (REU) programs. In the absence of the FSML network, with its wide range of funding sources, the cost of operating many of these national programs would be prohibitive. Consequently investments in FSMLs by NSF through programs such as the REU, LTER, NEON, FSML, and Major Research Instrumentation programs are highly leveraged, as are the investments of other granting agencies.

While the flexibility and highly decentralized nature of FSMLs allows for innovation and discovery, the lack of centralization poses challenges. Standardization can only happen to the extent that each facility and investigator individually agrees to those standards. Additionally, decision-making about the allocation of resources to various projects, such as long-term monitoring or data management, will depend solely on the priorities of the individual FSML and/or the host institution. Most importantly, strategic planning for a network of FSMLs requires considerable forethought and effort, as the NEON and LTER programs have demonstrated. However, the benefits of such coordination can be high, as the NEON and LTER programs have also demonstrated.

Despite the investment by a broad range of funders in FSMLs and the highly decentralized nature of the network, government engagement is still essential. Governments have to play a central role in facilitating innovation (NEC 2011), particularly given the importance of environmental processes to economic progress and quality of life, and the lack of simple pathways by which most ecosystem services are monetized. Funders can use their seed money to increase the scientific value of FSMLs, as well as to encourage participation in national strategic objectives.

NSF's FSML program has been particularly effective at this. Planning grants are a cost effective way to make individual facilities more effective and also help raise the profile of FSMLs within the host institution. Additionally, review criteria that emphasize the extent to which FSMLs serve as a platform for use by scientists from multiple institutions, and that include participation in national initiatives such as data management, are also cost effective ways to harness the resources of individual FSMLs towards strategic objectives.

One final idea that should receive further consideration is the establishment of a national Center to maximize the value of the FSML network. This was the most talked-about idea at the Colorado Springs workshop (NAML and OBFS 2013a). We recommend the establishment of an executive committee composed of leaders in the OBFS and NAML communities to pursue this vision and develop both detailed recommendations and a proposal for potential funding mechanisms. Given the scientific value of, and the large existing investment in, FSMLs, such an investment would unleash considerable scientific potential. Indeed, given the urgency of our environmental challenges, society has no choice but to ensure that FSMLs are highly effective institutions working towards national objectives. FSMLs must continue to generate discovery, enable sustainable human systems, and train a scientifically literate citizenry capable of meeting our oncoming challenges.

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APPENDIX: GLOSSARY OF ACRONYMS

AAAS	American Association for the Advancement of Science
COSEE	Centers for Ocean Sciences Education Excellence
DataONE	Data Observation Network for Earth
FSML	Field station and marine lab
GBIF	Global Biodiversity Information Facility
GEO BON	Group on Earth Observations Biodiversity Observation Network
GLEON	Global Lake Ecological Observatory Network
IOOS	Integrated Ocean Observing System
LTER	Long-Term Ecological Research
NADP	National Atmospheric Deposition Program
NAML	National Association of Marine Laboratories
NEPA	National Environmental Policy Act
NEON	National Ecological Observatory Network
OBFS	Organization of Biological Field Stations
OOI	Ocean Observatories Initiative
STEM	Science, Technology, Engineering, and Mathematics
UNOLS	University-National Oceanographic Laboratory System