Building and Operating the Field Stations and Marine Laboratories of the Future

A workshop hosted by the National Association of Marine Laboratories and the Organization of Biological Field Stations

Colorado Springs, Colorado
November 17–18, 2011

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Introduction

Dealing with dramatic and global environmental change is the challenge of our generation. Climate change, land use change, and invasive species are altering the ecosystem services upon which we depend (Millennium Assessment 2005, NRC 2004). To manage those services—which provide economic benefit on the order of, or even greater than, traditional economic activity (Costanza et al. 1997, NRC 2004)—we need to understand how ecosystems work, now and in the face of accelerating change.

Field stations and marine laboratories (FSMLs) stand at the heart of understanding environmental processes. As institutions that support sustained, place-based field research by multiple investigators, FSMLs provide

- insight into fundamental and complex environmental processes;
- a baseline from which to detect, interpret, and predict environmental change;
- education to ensure a scientifically literate citizenry;
- direct engagement between scientists and the general public.

FSMLs represent a substantial standing investment, from their physical plants and land-holdings to their administrative structure—and partly because of this, they can have considerable inertia. Science, on the other hand, is dynamic. What scientists want to do, and what they are capable of, is constantly changing. To narrow the gap between investment and innovation, the National Association of Marine Laboratories (NAML) and the Organization of Biological Field Stations (OBFS) are engaged in a strategic planning effort to position marine labs and field stations to meet emerging scientific and societal needs.

As part of that strategic planning process, with the support of the National Science Foundation, a steering committee of seven current and past presidents of OBFS and NAML (see Appendix A) conducted a workshop in Colorado Springs, Colorado, November 17–18, 2011. The goal of the workshop was to engage a broad community of scientists and field station personnel in conversations about the role FSMLs will play in addressing critical emerging scientific issues. Sixty-two scientists, directors of FSMLs, educators, and conservation stewards (see Appendix B) were organized into five working groups (Environmental Change, Molecular Biology and Genomics, Organismal and Population Biology, Ecosystem Dynamics, and Macrosystems) and two cross-cutting theme groups (Education and Outreach, Resource Management). Prior to the workshop, each working group chair facilitated telephone and online discussion among the group's participants to begin to identify significant emerging issues and productive areas of interaction. At the workshop, the working groups met independently and periodically reported out in plenary sessions. They also met in pairs at two separate "mashup" sessions to maintain communication across groups. The workshop agenda is provided in Appendix C.

Here we report on the proceedings of the workshop. We organize the major points brought up in each working group and cross-cutting theme discussion into sections on (1) the unique attributes of FSMLs that address each topic, (2) the emerging issues identified by each group, and (3) future directions the group envisioned. Exchanges between the groups during mashup sessions are integrated into the individual working group reports. While the workshop encouraged wide-ranging conversation, we have structured the report to focus on the role FSMLs will play in addressing emerging issues. This report is meant to capture those discussions, but not to analyze them or offer recommendations. The steering committee will deliver a separate final report containing a series of recommendations generated using input from the workshop, survey data from FSMLs, and broad input from the larger stakeholder community of FSMLs (Billick et al. 2013). What follows is an account of the dialogues at the OBFS and NAML workshop on Building the Field Stations and Marine Laboratories of the Future.

Figure 1. NAML-OBFS workshop attendees

1. Environmental Change Working Group

Global change is profoundly local. It affects each place in its own way, leaving local systems with new temperature and rainfall patterns, new chemistries, and new complements of species, interacting at various scales with other places and regions. The Environmental Change working group chose to center their discussions around previously identified grand challenges in environmental sciences (NRC 2001) and sustainability (Reid et al. 2010), and the contributions that field stations and marine labs can make to address them.

1.1. Unique attributes of FSMLs

Field stations and marine labs are an invaluable resource for assessing the impacts of environmental change at both local and continental scales. They provide long-term place-based data, and—with hundreds of facilities distributed across the country—can help address large-scale issues that vary greatly among geographic and climatic regions. There are four salient advantages of addressing environmental change issues through FSMLs:

1. *FSMLs often have invaluable legacy datasets* which provide important context for understanding baseline conditions through which environmental change can be studied.

2. *FSMLs provide an existing infrastructure* with laboratory and living facilities in key habitats distributed across the country. Using FSMLs thus greatly reduces the need for investment in bricks and mortar, enabling more resources to go towards the science.

3. *FSMLs are educational institutions* where scientists are both inspired and educated with immersive, hands-on experiences dealing with important ecological and environmental issues. Most FSMLs are linked to local University-level teaching and research. As place-based sites, FSMLs provide the space for face-to-face discussions which are critical for successful collaborations. These sites provide the common grounds for the development of cross-disciplinary communication, trust, and development of new collaborations and friendships.

4. *FMSLs are closely linked to the public.* FSMLs are a part of the local community for many decades, often developing a close relationship with local and regional residents that facilitates widespread and uniquely effective public education through both in- and outreach. This is essential for reducing the growing public confusion about ecosystem science that stems from inadequate understanding of the scientific process. Rather than outsourcing studies of large-scale regional or national import, FSMLs can fully engage the public and help them to understand local issues that can contribute to larger scale regional or national environmental change challenges.

1.2. Emerging issues

The global human population currently faces many serious challenges, from climate change, invasive species, and land use change to the grand challenges in environmental science identified by the National Research Council (2001). The Environmental Change working group used these as the basis for their discussions, and agreed with the Ecosystem Dynamics working group that the recently proposed grand challenges in earth system science for global sustainability (Reid et al. 2010), which are specifically targeted at interactions between human and natural systems, would be another useful framework. Here we identify some of the emerging issues and grand challenges in environmental change, and the contributions that FSMLs can make or have made towards addressing them.

Invasive species (NEON 2006)

Environmental change drives changes in species distribution and the invasibility of ecosystems. Both aquatic and terrestrial ecosystems across the country, and indeed around the world, are experiencing the spread of invasive species. FSMLs typically include local experts who can identify spreading fronts and simultaneously engage students and the public in research and education through student internships, volunteer monitoring networks, and interactive visualization tools.

Questions:

- How do different environmental change factors influence the success and the rate of invasions?
- How do invasive species affect ecosystem structure and function over long periods of time?

Biological diversity and ecosystem function (NRC 2001)

Biodiversity enhances ecosystem reliability, and varies across systems and over time. Biodiversity is being radically depleted by changing land use and climate. Loss of biodiversity has serious effects on local ecosystems, and consensus is developing that global climate changes are likely to have important regional consequences for biota and ecosystems.

Questions:

- What is the magnitude and extent of biodiversity change across the nation and across ecological systems?
- How does biodiversity change affect energy flow, nutrient flux, ecosystem resilience, or the transfer of information in freshwater, marine, and terrestrial ecosystems?

Biogeochemical cycles, climate variability, and hydrologic forecasting (NRC 2001)

Biogeochemical cycles cross ecosystem boundaries, necessitating cross-ecosystem study to fully understand cycle complexity, sources, and sinks. Environmental changes can affect biogeochemical cycles with important implications for both natural and anthropogenic systems. One of the clearest yet least understood biogeochemical signals of environmental change is the widespread changes in dissolved organic matter in aquatic ecosystems in many regions of North America and Europe (Monteith et al. 2007). In some cases as much as a doubling in dissolved organic carbon (DOC) concentrations has been observed (Monteith et al. 2007). The source of this DOC is adjacent terrestrial watersheds, but the drivers of the terrestrial changes have not yet been identified, and are likely to vary by region and ecosystem type. For example, mobilization of terrestrial carbon aggravated by the observed increases in extreme precipitation events observed in recent decades (Karl et al. 2009; Zhang et al. 2010) may be the source. This change could ultimately contribute to reductions in one of the largest global carbon sinks, soils. A different mechanism for the changes in DOC may be recovery from acid deposition as a result of the enactment of the Clean Air Act Amendments of 1990 (Monteith et al. 2007, SanClements et al. 2012). The recognition of these large changes in DOC were made possible by the use of long term datasets, many of which are located at FSMLs (e.g., Zhang et al. 2010). With the addition of buoy-based sensors in collaboration with other environmental networks such as GLEON, many FSMLs are well positioned to address both the causes and implications of these changes in DOC and dissolved organic matter as they have existing facilities and access to key and often protected lakes as well as coastal ecosystems.

Questions:

- How are biogeochemical cycles and nutrient fluxes changing in response to new hydrological regimes?
- What are the biotic consequences of climate-driven changes in biogeochemical cycles and hydrologic forcing?
- At the continental scale, how are major climatic variables changing (mean, variability, frequency of extremes)?
- How accurate are our predictions about the impact of climate change on ecosystem structure and function?
- How do extreme events affect ecosystems?

Infectious disease and the environment (NRC 2001)

Both the spread and vectors for infectious disease have complex linkages to abiotic and biotic environmental conditions (e.g., Lyme disease as controlled by oak mast, mice and deer populations, and forest fragmentation). System-wide, long-term and spatially explicit data from FSMLs are crucial for understanding linkages among disease "systems," and for predicting their spread. Downstream impacts, feedbacks, and connections among atmospheric-terrestrial-aquatic systems can be examined through FSML networks. In addition, a coordinated network of FSMLs could rapidly mount a program to assess the spread of emerging disease (e.g., spread of white-nose syndrome in bats).

Questions:

- How do the effects of forest pathogens in surrounding watersheds affect loading of DOC and nutrients to streams and lakes?
- How do forest pathogens affect other disturbances, such as fire?
- What are the subsequent effects on parasites and pathogens in lake ecosystems as a function of altered UV transparency?

Land-use dynamics and consequences (NRC 2001)

Often the effects of land use can only be recognized with the use of long-term datasets due to processes such as lagging effects. Additionally, the effects of land use modification may vary by region due to geology, precipitation, temperature, etc. Thus, FSMLs and their long-term datasets are uniquely poised to address the nature of land use dynamics as well as the effects of these changes.

For example, research at FSMLs demonstrates that land use changes have led to extensive eutrophication of both coastal and inland waters with consequent increases in harmful algal blooms (HAB) and severe oxygen depletion ("dead zones"). The Harmful Algal Bloom and Hypoxia Research and Control Acts (HABHRCA) of 1998 and 2004 identify HABs and oxygen depletion of coastal and inland waters as key environmental challenges and mandate research on aquatic ecosystems to address these issues.

Most FSMLs have associated aquatic ecosystems, often accompanied by long-term datasets that can be used to address changes in HABs and the development of dead zones in coastal and inland waters. With the addition of buoy-based sensors in collaboration with the Global Lake Ecological Observatory Network (GLEON) and Integrated Ocean Observing System (IOOS), many FSMLs are well positioned to address these issues as they are existing facilities with wide spatial distribution and have access to key and often protected lakes as well as coastal ecosystems. Networked FSMLs may yield new insights about the downstream impacts of upstream changes in land use.

Questions:

- What are the thresholds that lead to HABs?
- Is there a role that FSMLs can play in monitoring HAB factors along pathways to prevent or reduce their magnitude?

Develop, enhance, and integrate observation systems to manage global and regional environmental change (Reid et al. 2010)

FSMLs offer a unique and immersive nationwide facility for addressing issues in sustainability because they
(1) are associated with universities and have experts in economics, business, and the social sciences as well as natural and applied scientists and engineers to form the teams necessary for addressing sustainability issues,
(2) have facilities located in key natural habitats where impacts of the grand challenges are often highly visible and measurable, and (3) have the opportunity to connect with the public by engaging local residents in this immersive, dynamic environment.

Questions:

- What is the spatial and temporal extent of a particular environmental change? If this local system (e.g., stream) changes, what will be the consequences at larger spatial scales (e.g., for ecosystems linked via migration routes, flowpaths of water, particles, and solutes)?
- What is the degree of coherence among sites from local to regional to continental scales?
- Are there non-linear interacting effects between climate oscillations and environmental change that lead to thresholds?

1.3. Future directions

There are multiple mechanisms available to leverage the unique strengths of FSMLs to address these grand challenges. FSMLs are unique in that they are place-based, face-to-face facilities where environmental science is carried out in the midst of the natural world. These facilities are critical for fostering collaborations, and understanding site-specific rates, processes, and linkages. These sites have close connections to communities of academics, students, and the public.

Network Center

For many years both OBFS and NAML have served their members as a virtual network, with annual and other occasional meetings to provide the face-to-face interactions that sustain relationships among people who are dispersed across the country. Emerging national scientific needs for large-scale environmental experimentation and assessment have stretched the virtual nature of the FSML network to the maximum. FSMLs have the unique capability to act as an informal network of people to conduct collaborative science in addition to infrastructure networks that can be provided through programs like NEON, OOI, and IOOS. Further progress in addressing these critical national needs can be greatly facilitated by creating a new national center for field stations and marine laboratories which could provide a platform for people to meet and exchange ideas and develop common protocols and standards. A national center for field stations and marine laboratories would

- improve efficiency in many FSML endeavors by sharing resources, expertise, and reducing duplication;
- facilitate and encourage collaboration within the intellectual community that results in improved science;
- provide a central repository for the catalog of legacy data as well as current and future data collected at FSMLs. Some of the older datasets are still of great importance but are not well documented or archived. They sit in field notebooks and photographs in file cabinets and shoeboxes around the country, and are in danger of being lost as facilities close or individual scientists' careers end. Often, the value of disparate datasets can be greatly improved by connecting these datasets with similar datasets at other sites;
- provide a central place where training in all aspects of FSML operation and related scientific endeavors can take place;
- provide a centralized location for the dissemination of scientific results from FSML work to many different venues, in many different formats. Most dissemination will be electronic, but some might be the development of displays, brochures, video files, etc.

The national center should

- be a permanent physical place, with a strong digital presence;
- be centrally located near a major airport;
- have full-time staff.

A national center could address a broader set of scientific questions than individual FSMLs alone. For example, it could

- provide the ability to address scaling questions in a hierarchical way. Networked FSMLs fill in a spatial scale between that of (continental) NEON and (place-based) LTER sites and individual FSMLs;
- better integrate field stations and marine labs to ask scientific questions from catchment to oceanic basins. The diversity of sites is unique in that it spans even beyond continental (NEON does not include a marine component);
- ask questions that cover critical ecosystem gradients;
- help conceptualize and initialize large-scale research projects by bringing together scientists from across the country who are exploring similar scientific questions that require multi-site comparisons;
- provide the human network necessary to gain access to data, including legacy data;
- facilitate interactions in a network of networks, like the National Phenology Network.

In this vision, the national center would be a facilitator to answering key questions driven by investigators at the individual sites. Similar to the LTER system, the center would help researchers deal with the logistics of science, analysis, and writing, but would not dictate the questions or methods.

Education and in- and outreach

How can field stations better educate students to help them understand the enormity of the processes, causes, and impacts of anthropogenic environmental changes? To contextualize environmental change, FSMLs could

- provide environmental change datasets that could be used by teachers and professors to support curricular innovation (used on- or off-site) across disciplines;
- build a portfolio of place-based environmental change case studies for education and outreach;
- create protocols and provide equipment for a set of common field exercises that could be deployed across a network of FSMLs (similar to Bowne et al. 2011).

How can FSMLs better serve as centers for outreach? Because FSMLs are place-based and face-to-face, they can bring people in, emphasize hands-on science, and leverage virtual experiences to encourage future on-site engagement. FSMLs could

- engage K–12 teachers in science through continuing education credit, teacher workshops that increase content knowledge, and involvement in research (e.g., NSF's Research Experience for Teachers program (RET)). The Columbia University program provides evidence that this works;
- create environmental change datasets that could be distributed to and used by teachers, since federal education standards dictate that students need to graph, and FSMLs have real data;
- connect scientists to the community.

The integration of citizen-driven questions into the directives of FSMLs is vital to the development of a working relationship with the local public and citizenry. Questions from the general public ("in-reach") can serve as the basis for the development of directed place-based efforts or research that needs to be addressed through the network of FSMLs.

To this end, FSMLs could network with existing local, state, regional, and national entities. State and regional agencies receive questions regularly from the general public and tend to have a finger on the pulse of the environmental interests of the public, especially the fishers, hunters, and others who utilize ecological resources and services.

Most likely partners include:

- Coastal Resources Division, which provides fishing licensing and watercraft registration

- State Departments of Natural Resources, which provide access to fishers, boaters, and tribal organizations
- State Fish and Wildlife Agencies, which manage hunting and freshwater and saltwater fishing licenses/permits, and receive reports of fish kills
- National Oceanic and Atmospheric Administration/National Marine Fisheries Service—bluewater recreational fishers

To excite support for FSMLs, connect people to the environment around them, and engage the general public in discovering how they know what they know, FSMLs could

- provide venues (or links to venues) for the public to submit scientific observations;
- identify the target audience and communicate accordingly (e.g., create different programs for hunters and anglers than for technophiles and app developers);
- raise public awareness about science by, for example, hosting open houses, local business breakfasts, or meetings for local civic groups;
- provide compelling local and global examples of environmental change;
- connect weather station data from field stations and coastal observing systems to local media (e.g., TV);
- maintain networks of sensors in the community, possibly at schools;
- create a traveling display for the public with examples from different FSMLs.
- connect to the "gray" community through the history of the site, volunteer opportunities, or StoryCorps-like exchange of experiences;
- create a "Shadow the Scientist" Day.

2. Molecular Biology and Genomics Working Group

Rapid progress in genomics and molecular biology presents an opportunity for FSMLs to explore previously unseen aspects of otherwise well-covered territory. This working group focused on how FSMLs could promote discovery in molecular biology and genomics, and on the progress biology could make by integrating emerging molecular tools with field research.

2.1. Unique attributes of FSMLs

1. *FSMLs provide access to natural environments,* embedding scientists in the ecosystem for the long term.

2. *FSMLs create economies of scale* for visiting scientists, including dealing with acquisition and maintenance of equipment. They facilitate field collections at every stage, from arranging for sampling permits to freezing those samples to shipping them offsite (or in some cases, processing them on site).

3. *FSMLs often have background physicochemical data*—increasingly from embedded sensor networks—that provide context for interpreting findings, and which might otherwise have to be collected separately for each project.

4. *FSMLs are a test bed for evaluating new technologies* because of their existing infrastructure and contextual knowledge.

5. *FSMLs are conducive to interdisciplinary work*. When people study the same ecosystem, even if they take 10 different approaches, they have a common interest that provides an opportunity to collaborate.

The working group recognized the enormous diversity among FSMLs. Some host only a few visiting scientists for a few months; some have many resident faculty and operate year-round. The group emphasized that any strategic plan should take such variation into account.

2.2. Emerging issues

The opportunity to work across scales of biology from the molecular to the ecological opens up new fields of inquiry. Individual genes can be studied in the context in which they evolved. The genomes of non-model organisms can be sequenced and studied functionally in their natural habitats. Even the full genomic complement of entire communities of microbes—which may mediate environmental change in unknown ways—is now accessible.

The invisible ecosystem

Microorganisms run many of the planet's biochemical processes. The gases they emit contribute as much or more to the atmosphere as do all the plants of the world (Atlas and Bartha 1997). But since they are too small to see, we know very little about them—not even how many there are, what kinds, or where. Molecular biology and genomics are the most efficient tools with which to interrogate the microbial world, and this working group explored the sort of discovery that integrating molecular tools into field-based ecological research will make possible:

Microbial diversity, distribution, and abundance

The number of microorganisms scientists see in a milliliter of seawater has increased a thousandfold. Marine microbiologists are ahead of terrestrial ones in applying genomic techniques to describe diversity (International Census of Marine Microbes). Terrestrial work seems to focus more on function (Earth Microbiome Project).

Microbial role in ecosystem functions and services

Microbes perform major biogeochemical transformations, regulating nutrient flows and the release of carbon from terrestrial systems. It is possible that persistent mysteries of ecosystem dynamics could be solved by integrating future discoveries in microbial ecology into models of ecosystem function.

Microbes as sentinel species or communities

Microbes are very dynamic communities, and they respond quickly to perturbations. Evidence of the impacts of environmental change may appear in microbial communities long before macroscopic organisms respond. Microbes could turn out to be the best bioindicators.

Microbes as mediators of environmental change

Biogeochemical changes affect microbial community composition and structure, which in turn affect biogeochemical processes. Understanding these feedback loops could help predict ecological responses to environmental change.

Because microbes evolve quickly, they may also adapt faster to environmental change. Coral endosymbionts, for example, are more sensitive to heat stress than their hosts—which is an ecological disaster, but also possibly an evolutionary boon. Higher turnover means faster evolution; and even in the midst of global die-offs, it turns out that some corals' ranges are rapidly expanding.

Could microbes be important to mediating responses to environmental change even for macroorganisms? There is a growing appreciation that all organisms are complex ecosystems of genetically distinct cells, integrated to different extents. Microbes in the human body outnumber our own cells ten to one and have enormous impacts on our health. It may turn out that microbial DNA contributes as much to the physiology, development, and survival of plants and animals as do the host genomes themselves.

Real-time monitoring

With the development of more sophisticated automated sensing, there are more opportunities to integrate real-time environmental data with molecular biology. Rapid changes to the environment can serve as natural experiments to explore how the system works. What genes are expressed, in what organisms, at what points in the cycle of disturbance and recovery? Functional genomics could ultimately be monitored at marine labs in real time, linking continuous biological measurements with continuous physical ones.

Metagenomics of an island

Metagenomics extended the analysis of all the DNA in an organism to the analysis of all the DNA in a microbial community. The next step is to sequence all the DNA in an ecosystem, from the top predator down to the top predator's gut flora. It would also be interesting to look at the distribution of species diversity across taxonomic scales. Are there always more microbes than anything else? Does the distribution vary across time or ecosystems, and is it informative as a diagnostic tool?

Functional genomics of non-model organisms

High-throughput sequencing and other advances make it practical to extend genomic techniques to ecologically important systems. Model organisms such as Arabidopsis and fruit flies have been critical to progress in genetics, and the functions of many of their genes have been inferred in the laboratory. But fruit flies did not evolve in the laboratory. Now that it is possible to develop functional genomic tools for non-model organisms, the genetic basis of fitness-related traits can be approached at genome-wide scales in an organism's natural habitat.

2.3. Future directions

Bioinformatics

Field stations and marine labs need to transition into the era of data intensive science; staffing at FSMLs will need to reflect that transition. The working group considered strategies for bioinformatics education. Is it better to train biologists in informatics or computer scientists in biology? The general sense was that it is easier to train a biologist on informatic tools than it is for an informatician to understand enough of the biology to develop meaningful analyses. Adapting to the data-intensive nature of field research will also require maintaining the appropriate onsite data infrastructure, developing appropriate standards for data and metadata, and ensuring that communities developing standards (Genomic Standards Consortium (GSC), Biodiversity Information Standards (TDWG), Ecological Metadata Language (EML)) have fully incorporated the unique needs of field data.

Network
The Molecular Biology and Genomics working group was not as enthusiastic about the blanket need for networking as were the other working groups. A few specific goals for which the group suggested networking would be useful include systematizing sample collection pipelines, organizing biorepositories, and increasing efficiency in cyberinfrastructure development.

Comparisons across stations could be very valuable, but the FSML network needs to know what capacity exists at which stations, what archives each has, and how their approaches differ. Not all labs are equipped for all protocols.

Terrestrial genomics
The application of genomics seems to have lagged behind at field stations compared to marine labs. A few "aha!" moments helped stimulate marine microbiology, like the metagenomic sequencing of seawater and the discovery of microorganisms living in thermal vent environments. Terrestrial microbiology needs the equivalent catalysts. Identifying molecular methods that would be useful for field biologists, and ecological questions that genomics can help answer, could also spur discovery.

3. Organismal and Population Biology Working Group

Individual plants and animals can respond to a changing environment by altering their physiology or behavior, by moving away, or by dying. Populations can respond by shifting their ranges or by evolving. Field stations and marine labs are the front line of discovery for the relationship between organism and environment.

The Organismal and Population Biology working group identified emerging issues in the field related to fundamental science, to environmental change, and to societal needs. They also proposed an organizational structure for a potential national network center for FSMLs.

3.1. Unique attributes of FSMLs

1. *FSMLs provide access to the environment.* They are located for the most part in natural settings, allowing scientists to assess the impact of environmental change within a natural context and with the benefit of longitudinal records.

2. *FSMLs facilitate interdisciplinary interaction.* The presence of multiple research groups with backgrounds in different disciplines all studying the same place creates a kind of collisional commons from which novel ideas and approaches emerge.

3. *FSMLs are immersive educational institutions* that foster intellectual community and promote experiential learning.

The working group initially approached the question of FSML's societal impact using the four major themes identified in the NRC's (2011) "Critical Infrastructure for Ocean Research and Societal Needs in 2030" report: enabling stewardship of the environment, protecting life and property, promoting sustainable economic vitality, and increasing scientific understanding. The public cares about safe water, safe air, and safe food. Field stations and marine labs are best suited for the following issues and opportunities:

- Enhancing scientific literacy on the roles biodiversity and ecosystems play in sustaining economic vitality and property
- Training scientists
- Connecting with urban populations
- Connecting with coastal settings
- Creating learning moments
- Inquiry-based experiential learning for the public, in part to create a sense of ownership that encourages stewardship
- Curating historical data and collections to provide critical information for future planning as well as context for current and emerging issues

3.2. Emerging issues

How do organisms, populations, ecosystems, and global societies respond to the rapid and accelerating pace—and increased inter-annual variation—of environmental change?
The Organismal and Population Biology working group identified particular drivers of environmental change, as well as particular responses to it, as critical emerging issues.

Drivers:

- Changing climate
- Changing phenologies
- Fragmentation, habitat loss, habitat degradation
- Severe events (natural and man-made)
- Invasive species
- Exploitation
- Loss of genetic diversity and biodiversity
- Loss of apex predators (except humans)

Responses:

- Empirical studies of population, community, and ecosystem dynamics and connectivity*
- Phenologies (e.g., flowering, spawning, hibernation, etc.) and consequences*
- Invasibility and response to invasive species*
- Geographic shifts*
- Phenotypic plasticity and adaptation*
- Changing ecosystem function and services*
- Alteration of trophic dynamics*
- Social and economic change (e.g., changing resource use)*
- Community genetics
- Disturbance of co-evolutionary dynamics
- Local and global extinctions
- Loss of genetic diversity and biodiversity
- Resource management
- Emerging pathogens

* Responses identified with an asterisk are especially relevant to FSMLs.

What are the linkages among genes, phenotype, environment, and fitness?
The working group also highlighted some of the fundamental science to which FSMLs, as the link between lab and field, are essential:

- Gene expression in the environment (functional genomics)
- Natural selection and adaptation

What are key sentinel species in different systems, and how can they be used to understand and predict responses to environmental change?

How do we maintain expertise in natural history and systematics?

How do we integrate natural and social sciences effectively?

3.3. Future directions

The following are critical components of FSMLs that can serve emerging needs in research, education, and resource management:

- Network infrastructure
- Controlled environmental systems (mesocosms, greenhouses, seawater systems)
- Human resources (traineeships, education specialists)
- Cyberinfrastructure (hardware and software)
- Accommodations for visiting scientists and students
- Vehicles and vessels for sampling
- Sensors
- Lab equipment
- Shared digitized archival datasets

The following are critical gaps in knowledge:

- Quantitative assessments of the value of experiential learning (perceived benefits, perception of rigor)
- Awareness of and access to long-term databases (digitized archival databases)
- Where are transect- and plot-based opportunities to study change? Examples include
    - the Hewatt transect, a 1931–1933 baseline study of the rocky intertidal at Hopkins Marine Station (Sagarin et al. 1999);
    - the Nenana Ice Classic in Alaska, a contest to predict the timing of river ice breakup in which people have been betting, and keeping records, since 1917 (Sagarin and Micheli 2001);
    - colonization experiments begun in 1971 beneath the Duke University Marine Lab dock (Sutherland and Karlson 1977).
- Urban systems are not well represented in research studies or questions

Network Center

Chief among considerations in this working group was creation and organization of a national FSML network center. Such a center would leverage existing infrastructure and human resources to undertake coordinated studies of continental-scale issues as a complement to national investments in observatories such as NEON and OOI. A center would also facilitate strategic planning to define and achieve goals; facilitate international networking; and provide an opportunity for terrestrial, aquatic, atmospheric, and marine systems integration.

The group envisions an inclusive virtual federation among FSMLs, with a physical network center that would interact effectively with other kinds of networks including NEON, OOI, IOOS, DataOne, and the World Network of Biosphere Reserves. The NASA Astrobiology Institute is a potential model for some center characteristics. In terms of intellectual leadership, developing a roadmap that guides research and database development across FSMLs towards a set of three or four priority issues that can best be tackled through a coordinated effort by subsets of FSMLs would allow the center to develop a focus, achieve one or more objectives, and look to build its portfolio over time. The network roadmap would be supported by cyberinfrastructure, education, standards, and assessment.

4. Ecosystem Dynamics Working Group

Ecosystems integrate processes occurring at all levels, from microbial metabolism to population migrations, and their dynamics indicate how whole systems are responding to changing environments. The Ecosystem Dynamics group discussed emerging trends in monitoring and experimentation, and the increasing need to predict and manage environmental change. They ultimately chose as their framework the grand challenges in earth system science for sustainability (Reid et al. 2010), to focus on science that would have the greatest societal impact.

4.1. Unique attributes of FSMLs

1. *FSMLs have legacy data* that provide context for interpretation of new patterns or findings.

2. *As place-based institutions*, FSMLs can help make regional climate forecasts locally relevant.

3. *FSMLs are bridges between the lab and the field* that can host replicated, controlled perturbation experiments to test whole-ecosystem responses (mesocosms).

4. *FSMLs provide data for the development and validation of models* through both sensor-based and human observation.

5. *FSMLs are a national platform to develop new technology and capacity.* They are ideal locations for ground-truthing remotely-sensed data and for sensor development and testing.

4.2. Emerging issues

Monitoring and remote sensing

One of the biggest opportunities for FSMLs to contribute to transformational science is through monitoring and remote sensing. The technology for environmental sensing and wireless sensor networks is now mature enough for large-scale deployment. Some individual sites already have high-frequency automated sensor arrays linking air, water, soil, and plants and laid out across landscapes. Regional and national networks are beginning to emerge with the goal of making the data available in near real-time to ecosystem modelers and to the public. This will help develop more predictive capacity by providing data to test, inform, validate, and improve existing models of ecosystem interactions.

Long-term ecosystem studies that are not sensor-based also continue to provide insight into both local and larger scale phenomena. The serendipitous discovery of acid rain at Hubbard Brook Experimental Forest spawned decades of national research and policy changes. More recently, studies of forest ecosystems (e.g., Jensen et al. 2012), lake ice phenology (e.g., Beier et al. 2012), and other experiments involving human observation have informed sustainable resource use. Delving into the archives establishes the amount of variation that has been "normal" as well as how things are changing now. Long-term studies also provide a mechanistic understanding of ecosystems that can help forecast potential feedbacks and future conditions.

Mesocosms

Ecosystem-level perturbation experiments in replicated, controlled systems—mesocosms—are vital to advancing our presently limited understanding of ecosystem responses to climate forcings. By manipulating inputs and measuring outcomes at a larger scale, mesocosms take into account not only the factors and interactions that are already known to be important, but also those that are not. Mesocosms can reveal unanticipated tipping points and improve quantitative predictions of whole-ecosystem responses. In an arctic pelagic mesocosm, for example, the fate and effects of added carbon turned out to depend critically on the state of the microbial food web (Thingstad et al. 2008). Since FSMLs bring the laboratory to nature, they are by far the best places to directly test emerging regional and global theories of ecosystem response.

Molecular ecology and genomics

A whole-ecosystem approach in collaboration with biogeochemists and molecular biologists could open several ecological black boxes, including the function of chemical signaling and gene expression from an ecosystem perspective. Field stations also provide an ecological context for evaluating microbial and molecular data and patterns.

4.3. Future directions

Grand challenges in earth system science for sustainability

Human beings are an integral part of Earth's ecological systems. Studying ecology without studying human impacts and human needs won't get us very far towards understanding ecosystem dynamics (LTER 2007); and understanding ecosystem dynamics without understanding the political and social context in which they are embedded won't get us very far towards implementing sustainable solutions (Vaughan et al. 2007).

The ecosystems dynamics group considered socio-ecological goals as potential drivers for future research. The following questions (based on Reid et al. 2010) could guide FSMLs in meeting sustainability grand challenges:

- How can FSMLs improve the usefulness of forecasts of future environmental conditions and their consequences for people?
- How can FSMLs contribute to the development, enhancement, and integration of observation systems to manage global and regional environmental change?

- How can FSMLs help to determine how to anticipate, avoid, and manage disruptive global environmental change?
- How can FSMLs help to determine institutional, economic, and behavioral changes to enable effective steps towards global sustainability?
- How can FSMLs encourage innovation and mechanisms for evaluation in technological, policy, and social response to achieve global sustainability?

Networking

Networking FSMLs across larger geographic scales—across watersheds, for example, or from ridge to reef—would provide a broader context for research, and make FSMLs more effective as earth observation systems (OBFS 1999). A network center would allow rapid response to management initiatives, and to environmental disasters and extreme events. This could also include a longer-term response to biological invasions, as a network would allow tracking of invasive species across broad spatial scales.

Geospatial tools for data visualization are key to networking effectively and to conveying ecological information to managers and decisions makers. A network center could help develop and disseminate such tools.

The ecosystem dynamics group recommended a two-stage process for establishing a network. The first step is to know what is out there. A map-based geographic interface to identify the information (e.g., datasets) and infrastructure (e.g., mesocosms) available at each FSML would promote collaboration and the engagement of outside parties. Organizing the network into a series of regional groups (like WAML and NAML) may be helpful, but runs the risk of compartmentalizing.

The next step is to develop the technology and the incentives to share data across the network. The goal is a portal through which station and investigator data are contributed and accessed, ideally with middleware to harmonize the disparate data streams coming in and sophisticated geospatial and visualization tools to communicate the data going out. The University of New Hampshire 3D/4D visualization of marine mammal feeding is a good example of the latter.

For this to work, the culture of data sharing will have to change. FSML station data should be readily available. Individual investigator data should be shared on realistic time scales. LTER is a model for this. The FSML community could develop incentives to promote this cultural shift.

An example of open source geospatial data sharing between multiple partners and agencies is the Adirondack Park Regional GIS project (http://aprgis.org:8080/argis). The data producers manage and retain ownership of their data, and APR-GIS makes it available for display and query via a web portal.

Not every FSML has to do everything. Which stations are better at handling which problems? Large spatial and temporal scale questions can be answered more efficiently if the network strategically chooses who measures what.

Prediction

Forecasting future ecological conditions is complex; current models need more predictive capacity. Improving understanding of ecosystem interactions through data-intensive environmental monitoring and ecosystem-scale manipulative experiments will enable better ecological forecasts.

Communication and outreach

FSMLs should partner with organizations already involved in outreach, and establish evaluations for effectiveness of education, communication, etc. FSMLs could engage more effectively with multiple audiences, and should make creative use of multiple media, including online social networking and other web-based platforms.

Social scientists and economists can help address issues of sustainability; the arts and humanities can help communicate science in ways that reach new audiences. FSMLs benefit from cross-fertilization too, as incorporating multiple perspectives and ways of knowing can foster innovation.

5. Macrosystems Working Group

Local changes have regional- and continental-scale consequences and causes. The Macrosystems working group discussed how field stations and marine labs can contribute to understanding the effects of climate change, land use change, and invasive species across the broader landscape and through time.

5.1. Unique attributes of FSMLs

Individual FSMLs *facilitate comprehensive understanding of local environments* and have been collecting data for long periods of time; FSMLs as a network can contribute to regional, national, and global-scale research. The Macrosystems working group suggested several ways a network of FSMLs could complement continental-scale initiatives such as NEON:

The *broad spatial coverage* of FSMLs could

- facilitate scaling investigations;
- help fill in observational gaps in rapidly-changing areas; and
- provide more landscapes in which to detect anomalies and ground-truth remotely sensed data.

The *long-term datasets* at FSMLs

- provide the ability to look in the rear view mirror.

5.2. Emerging issues

The emerging scientific issues that extend to the broad geographic and temporal scales relevant to Macrosystems research include

- regional- to global-scale quantification of carbon cycling, storage, and dynamic temporal interactions with climate that reveals mechanisms and drivers;
- long-term effects of changing climate (over space and time), land use/cover, 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) 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.

5.3. Future directions

Macrosystems research programs at FSMLs must balance competing needs. The first need is for place-based research that contributes to the understanding of the local system; this requires flexibility of experimental design. In contrast, there is also a growing need to ensure that individual experiments and surveys can be scaled up, which requires the ability to standardize methods across FSMLs to maximize the contribution of individual FSMLs to regional, national, and global-scale research.

Field stations are key areas where science and management meet at the ground level. "No single question can serve as the only priority for FSML research," so other features of the stations contribute to the needs for new scientific efforts, including geographic location and its juxtaposition in the broader landscape, networking and collaborative programs among stations and other agency efforts, long-term data (point and spatial), comprehensive understanding of local environments, and capable data management activities.

Networking

There is a need for a well-orchestrated collaboration network that would help FSMLs identify other field stations conducting similar research, with the goal of allowing similar studies across locations to be used to address questions at larger spatial scales. FSMLs also provide a nexus for additional research locations within an ecosystem type or biome that can be networked to create a more representative realization of that ecosystem type. A national/international database of long-term research projects at FSMLs could maximize the value of individual research projects by providing more opportunities for collaboration with other locations conducting similar research. FSMLs could play a vital role as part of a network to gather the sufficient breadth and depth of data needed, the extent of which will be determined by the nature of the question. FSMLs could also help by developing trusted relationships with resource managers, engaging them in defining and interpreting research as well as developing education programs.

Macrosystems questions cannot be answered by studies at any single locale—it will take integration among FSMLs and among datasets from FSMLs and elsewhere. There is great value in replicating place-based research on ecological processes and in overlapping complementary research projects to minimize duplication of effort on shared data needs. FSMLs need to increase their collaborative efforts. This does not negate the need for individual projects in different places; the number of FSMLs is limited and can be augmented by other individual projects, especially if they occur along gradients of importance to the question. The key is collaboration, integration, and networking of these research efforts.

These goals could be served by the creation of a network center, which the Macrosystems group envisions as a service organization rather than a governing body. The center would have a physical office as well as a virtual presence, and should facilitate consensus building, governance, and community among FSMLs. The group discussed the qualities and the branding of a potential network center as well as its governance, funding, and roles.

During the mashup sessions, the Macrosystems working group discussed its vision of a formalized network with both the Environmental Change and the Ecosystem Dynamics working groups. Macrosystems noted that Environmental Change identified three categories of data the network could aggregate: (1) station collected and managed data, (2) proprietary data collected and controlled by researchers conducting research at FSMLS, and (3) external data that are collected and managed by entities/agencies located off FSMLs, but which FSMLs are aware of and potentially have access to through the unique partnerships and relationships that exist between the FSML and agency.

Macrosystems noted the merit of Ecosystem Dynamics' outcome-focused approach to networking, motivated not by specific emerging issues to which FSMLs can contribute but by where, in general, FSMLs can network to (1) better assess current effects, (2) improve forecasting, and (3) use data to create new knowledge that ultimately informs resource management.

Macrosystems disagreed with Ecosystem Dynamics on the point of certification by the FSML network center. Ecosystem Dynamics suggested that certifying individual labs or stations would improve data quality assurance/quality control. Macrosystems thought that requiring certification could unnecessarily marginalize and exclude FSMLs, and wants the FSML network to be as inclusive, transparent, and enabling as possible. Overall, though, the interests of the Macrosystems group are closely aligned with those of both the Ecosystem Dynamics and the Environmental Change groups, and are complementary with respect to the creation of a field station and marine lab network center.

Cross-scale/cross-site analysis using long-term datasets and remote sensing

While cross-scale and cross-site comparisons are common, it is rare to have long-term measurements to use for these comparisons. With environmental change, comparisons in space and time are more important than ever. FSMLs will remain important as sites for place-based, site-specific research on processes that drive the patterns observable in the remote imagery as well as in ground-truthing, especially if the station area is in a desired environment that cannot be found elsewhere. A location along an important gradient also will contribute to the value for remote-sensing approaches. They will always be important as places to verify actual field conditions and to calibrate data collected from remote sensors. Some features can only be detected on the ground (e.g. the presence of a given invasive species). Some features can be detected with remote sensors but must be calibrated using data collected on the ground (e.g. fuels conditions). Field sites are always going to be too complex to be able to rely solely on remote sensors. Linking space-based and ground-based data should be a major focus of macrosystems research. The interface with and use of remotely-collected data, including data from sensors and ground-based photos and videos, could also be improved.

Data-intensive science

In our rapidly growing information age, we are faced with massive and massively complex datasets yet the training and tools needed to convert these data into valuable information are sorely lacking. Data intensive science involves the ability to visualize, conceptualize, and discover patterns in massive datasets that can then be translated into information, policies, and planning. Better spatial thinking and geospatial tools are needed to provide critical space-time context for data and information.

Increasing the ability to harvest large data streams from the increasing array of environmental sensors and the geospatial opportunities for remote sensing of broader scales may be the most common opportunity/challenge among all stations. The following statement (Brunt and Michener 2009) is still largely true: "Four primary issues were identified as impeding the storage, discovery, and access of field station data: (1) insufficient network connectivity, (2) obsolete equipment and software, (3) inadequate data management and systems administration support, and (4) lack of training."

Survey

To assess the capacity of FSMLs to provide data in support of a network, information is needed on the resource, data, and institutional characteristics of the individual stations. Suggested survey questions follow:

1. Resource characteristics
   - Does the FSML have the ability to conduct experimental manipulations, or access to sites that do?
   - Where does the FSML fall on an urban–wildland gradient?
   - To what degree is the FSML experiencing the effects of land use change?
   - What is the FSML's geographic location?
   - What cover types, habitats, and ecological communities does it contain?

2. Data characteristics
   - Is the FSML currently doing long-term monitoring?
   - Do legacy datasets exist? If so, distinguish between abiotic and biotic datasets.
   - Does the FSML have species lists? If so, distinguish between flora and fauna datasets.
   - Does the FSML have a weather station? What variables are collected? Over what time periods are data available?
   - Does the FSML have share-able GIS layers?
   - Does the FSML have LIDAR coverage? If so, terrestrial or airborne?
   - Does the FSML have existing capacity to manage and share its data?

3. Institutional characteristics
   - What groups does the FSML partner with? (research institutions, state agencies, federal agencies, NGOs)
   - How is the FSML influencing policy locally, state-wide, regionally, and beyond?
   - How is the FSML being impacted by local and state policies?

6. Cross-Cutting Themes

Participants from several working groups (see Appendix B) regrouped to discuss two cross-cutting themes: Education and Outreach, and Resource Management. Their conversations are summarized below.

6.1. Education and Outreach

What do field stations and marine labs do well in education and outreach, and what could they do better? Participants had a wide-ranging discussion on what FSMLs have to offer, how networking FSMLs could improve their education and outreach, and how to get where they want to be.

Unique attributes of FSMLs

Field stations and marine labs offer opportunities for inquiry-based, experiential education. They facilitate the public's access to the environment and, unlike nature centers, they show science in action.

The culture of learning is very different at FSMLs. Visitors and students are immersed in the environment and in the scientific process for a period of time from a day to several months, watching (or actually doing) real ecological research. Because of the place-based engagement in a common system or problem, FSMLs are ideal centers for interdisciplinary study and for forming learning communities. Their size allows greater flexibility to experiment with new models of teaching and learning. They offer a wide range of mentoring opportunities. Especially at residential programs, and in contrast to the norm on main campuses, people all along the academic hierarchy—from established scientists to post docs to undergrads to high school students—interact freely with one another. The intensity of hands-on experiential learning leads to a greater sense of ownership.

More quantitative assessments of the effectiveness of experiential learning are needed. There are a lot of self-reports and anecdotal evidence, but not a lot of hard data on the impact of different field station programs on learning outcomes and career pathways. Recent studies at Jasper Ridge Biological Preserve are an exception.

As centers for outreach, FSMLs have a reservoir of knowledge about the local environment and become a trusted resource for the community ("what's this I found in my yard?"). They have the ability to implement high-quality citizen science initiatives. And their place-based nature makes FSMLs poised to integrate multiple ways of knowing and bring cultural relevance to science endeavors.

Target audiences

Aside from the undergraduates, graduate students, and postdocs that comprise the bulk of trainees at field stations and marine labs, are there particular audiences that FSMLs should be targeting?

FSMLs could offer hands-on research experience to community college students, whose institutions do not necessarily have the resources or the faculty to provide those opportunities. Community college students are an often-overlooked population. FSMLs tend to focus on biology majors, but the students who haven't made up their minds in the first two years are the ones it is arguably most important to draw into science career pathways; and for those that don't pursue science careers, the education they get in those early years will be the sum total of their scientific literacy. Community college students are also in general a more diverse audience than university students.

Other potential audiences include the home-school community, under-served populations in traditionally rural areas (including Native Americans), and under-served populations in urban areas. The urban group may be harder to reach, both geographically and culturally, though some FSMLs—such as Nantucket Field Station and the University of Cincinnati—have successful programs.

Recreational biologists and naturalists are another audience to consider, especially those who come to field stations and marine labs with a lot of natural history knowledge but without a lot of formal scientific training. These people may benefit most from the experiential approach to science education.

FSMLs should also reach out to political leaders at local, regional, state, and federal levels. It would be better to do this on an ongoing basis than to wait until their help is desperately needed.

Thinking farther out in outreach, FSMLs could consider global educational partnerships. For example, the elementary school online exchange program Windows Around the World tracks phenology with webcams in Massachusetts, Hawaii, Inuit villages, Trinidad and Tobago, and the Appalachians. Another program lets undergraduates in Kansas and at Kruger National Park in South Africa compare their grasslands.

Networking

Are there particular opportunities to support education that might come with networking, and what are they?

Some members of the discussion group have advanced their goals by networking with existing programs. Possible partners include:

- U.S. Department of Education's Upward Bound program
- U.S. Fish and Wildlife Service's educational branch
- other federal, state, and local agencies
- Ecological Society of America's Strategies for Ecology Education, Diversity and Sustainability (SEEDS) program
- Association for the Sciences of Limnology and Oceanography's Multicultural Program
- No Child Left Inside

Creating a formal network among FSMLs themselves could move education forward in several ways. First, a network would provide avenues for sharing the innovative, place-based, hands-on, exciting, straightforward, fun, and inexpensive educational activities that FSMLs design. Some marine labs are engaging the public in marine science education and increasing ocean literacy in very creative ways. A stronger network could help replicate these successes.

Larger-scale educational programs could also help attract educational researchers to the field. By implementing network-scale programs as educational experiments, FSMLs could produce the data necessary to assess the impact of experiential learning.

Advantages of networking for undergraduate education include the possibility of sharing common field exercises and of instituting comparative research projects—networked REU students could experience the collaborative nature of science. For graduate students, networked FSMLs would provide an opportunity to organize traineeships focusing on topics such as natural history, systematics, transdisciplinary studies, or the application of genomic tools to ecological questions. The NCEAS distributed graduate seminars are a possible model.

To make this kind of networking happen, FSMLs will need to invest in

- human capital
- cyberinfrastructure
- buildings and facilities (e.g., classrooms)
- protocols for effectively using social networking tools.

Incorporating online learning into field-based courses can maximize the time spent on the ground with experts at the location, and also extend the experience into the everyday lives of the students.

FSMLs are ideal arenas for linking science and education and for multidisciplinary training. Extending the web of FSML interaction across a network could enhance those strengths, preparing students—whether they ultimately go into science or business—for a culture of collaboration and for thinking flexibly across scales.

6.2. Resource Management

Data collected at the widely distributed array of field stations and marine labs (FSMLs) have enormous potential to inform resource management decisions in a variety of ways. Taking advantage of a network of widely dispersed and strategically located sites would enable research and monitoring that spans many ecological issues over regions, gradients, or even the entire country. The focus of the Resource Management discussion group was to determine how FSMLs can make meaningful contributions to practical challenges of natural resource management. This includes identification of a number of research or monitoring questions that (a) address the critical contemporary issues of land and resource managers and (b) are best suited to being addressed using an array of field sites with relatively modest capabilities but an extensive distribution.

The discussion group considered pertinent issues including the following: What are the information needs of land and resource managers today, and what might they be in the future? What questions are currently being pursued by FSMLs, and what questions have yet to be asked? For future projects, what kinds of incentives would help establish scientifically robust and persistent research? Are additional partners needed, beyond members of the Organization of Biological Field Stations and the National Association of Marine Labs? These considerations can help fashion a nexus between the interests and long-term objectives of FSMLs and the needs of resource management organizations.

Background

Ecosystems have changed more in the last 50 years than at any other time in human history, largely as a result of factors that operate at multiple spatial and temporal scales (Millennium Assessment 2005). It is now clear that local processes affect broad-scale ecological dynamics and broad-scale drivers can overwhelm local patterns and processes. Connectivity has been altered in unprecedented ways through human transport of propagules, toxins, and diseases, as well as anthropogenic disturbances and changes in land use.

Concurrently, the science of landscape ecology has evolved rapidly in the last two decades and has had a significant impact on the perspective that land managers have developed about how to plan and execute resource management actions. New analytical tools (e.g., GIS and remote sensing) have emerged in tandem with a growing awareness of and attention to scaling issues in wildland landscapes, which are being managed at multiple scales for the sustainability of a broad assortment of ecosystem functions.

These circumstances have spawned a suite of questions that spans substantially larger spatial and temporal scales than those previously considered by land managers. Issues such as climate change, invasive species, continued changes in land use status, and many others have bred numerous critical questions to which managers seek answers. These challenges will require additional and novel sampling designs coupled with innovative, state-of-the-art scientific infrastructure to gather the necessary data. The array of field facilities across the United States—including members of the Organization of Biological Field Stations and National Association of Marine Labs, but also potential partner networks such as the Experimental Forests and Ranges and the Research Natural Areas managed by the Forest Service—offers a potential platform for addressing many of these needs.

Emerging issues

Resource management issues are emerging that have not been encountered before and that have no obvious solutions. These relatively novel or accelerating challenges have to be addressed in management plans and project documents, and the public calls for scientifically supportable action. But the science is still relatively uncertain, and resource managers believe they do not have either the defensible information or the tools and guidance to take assertive action.

What is the best way to connect the sources of scientific information (e.g., field stations) with the demand for credible scientific information (e.g., resource managers)? FSMLs have specialized data that could fill a critical void, but resource managers tend not to come to field stations for help. Many managers might not know how to ask the appropriate questions or otherwise communicate with scientists; many scientists, in turn, do not make the time for or are somehow uncomfortable reaching out to managers. The opportunity is clearly there for FSMLs to play a pivotal role in informing resource management issues, but something has to change to support what could be a significant shift in the contributions that FSMLs can offer.

Managing land and natural resources in a changing world

Managing natural resources in response to a changing climate is an unprecedented challenge. Climate change affects everything; but how exactly it affects any particular place is still highly uncertain. Assessing the potential pros and cons of planned actions in this context becomes much more complicated. For every proposed land management project, plans must describe not only the existing environment and how the treatment would affect it, but also how the climate might change and how that change would affect the outcome of the treatment.

For example, across the western United States the Forest Service is managing for resilient forests in part by attempting to reduce fuels on landscapes that have been subject to fire suppression for decades. But in future forests, fire behavior will be different. Each landscape may experience, for example, less precipitation, more rain and less snow, or warmer and longer dry seasons; and those conditions will be different on a north-facing slope than a south-facing one. The many climate models that have been developed in recent years are helpful at a large, regional scale, but applying them at a finer scale is problematic. In light of uncertain, spatially variable, and rapidly changing conditions, what are the best forest management policies?

Forest managers have the opportunity to develop land management prescriptions that will make significant positive impacts on the health and resiliency of forested landscapes. With good research they can mitigate the effects of climate change through strategies that enable forests to better adapt to changing climates, for example by acquiring land to create corridors to assist species migration. They can even mitigate climate change itself, for example by minimizing high-severity fires that emit greenhouse gases, or through innovative silvicultural approaches that increase carbon storage and sequestration. Agricultural sustainability, too, depends on scientifically informed management.

These are critical land management considerations that require solid scientific evidence before managers can implement new strategies with confidence. This starts with reliable and relevant field data that leads to defensible scientific conclusions. What will the role of field stations be in informing this process?

Questions FSMLs could help resource managers answer

Field stations and marine labs already tackle some of the issues most important to resource management. They pursue questions that lead to development of an understanding of ecological processes and ecosystem drivers. They are ideal locations in which to develop and evaluate new technologies. They are equipped to monitor trends in ecosystem health and species composition, and could provide a suite of real-time information to resource managers to enable rapid response (e.g., to the arrival of problem invasive plants at a new location).

There is clearly an advantage of having a consortium of field stations—several hundred sites, well distributed across the ecological diversity of the continent—to assess conditions across a broad array of environmental settings. A number of easily measured features of wild landscapes can be good indicators of changing climate: precipitation, temperature, phenological parameters, stream flow, etc. Having a wide variety of field sites, in different geographic and topographic conditions, can be useful in teasing apart subtle differences in our observations of landscape conditions and responses.

Given the extensive distribution of field stations and marine labs across the country, they are in a unique position to provide advice to resource managers on the ongoing status of biological invasions. Relatively simple protocols could be used at large numbers of field sites to monitor the arrival of new invasive species and/or shifts in their relative abundance. This might help detect meaningful changes, in real time, while more control options are still available. Both new and historical species inventories could be very useful to generate maps of invasion. This may require some investment in specialized expertise, such as training in systematics and taxonomy. Field courses would be valuable, particularly field courses that would occur regularly (e.g., annually).

Another example of the kind of system-wide data collection that could be useful to land managers is the monitoring and reporting of vital signs (e.g., carbon flux, biodiversity, extreme disturbance events, interesting biological phenomena, local extinctions, phenology, etc.) at different field stations. There would need to be some discussion on (1) how to select and parameterize the appropriate vital signs depending on the question or ecological region in which the work is being done, and (2) how this information would be reported to and used by managers. The Report to the President on Sustaining Environmental Capital (PCAST 2011) provides a good example of how FSMLs might contribute to a report on the state of our environment every four years. Such a process could capitalize on the work of researchers taking the pulse of the environment in the intervening years.

FSMLs may also be able to make a contribution to national initiatives currently addressing conservation challenges over large landscape areas such as ecoregions. The Department of Interior's Landscape Conservation Cooperatives (LCCs) aim to change conservation trajectories at a regional level through a network of public-private partnerships providing science to resource managers. The Department of Agriculture has a similar initiative to encourage an "All Lands" approach to managing landscapes in which land managers can partner with adjoining land owners to work across jurisdictions and land-use types, viewing wildland landscapes as an integrated whole, both ecologically and socially. FSMLs could serve as a nexus for coordinating conservation-oriented activities in a given ecoregion.

Another consideration is a field station's influence on surrounding lands. Many field stations across the country are focal points for the scientific endeavors within a given community, including local human communities and diverse ownerships with similar land management challenges. How can field stations inform management in adjoining areas? Can FSMLs partner with public agencies and other owners of adjacent land to support land management decisions on these holdings? This is a potential opportunity that merits further exploration.

Future directions

What needs to happen for FSMLs to become better stewards of the wider environment and make a broader contribution to resource management? The discussion group identified actions that would bring FSMLs closer to advancing the goals of resource managers and to taking full advantage of the range of available resources that exist at field stations and marine labs.

Networking

First, it would be helpful to develop a database of who does what research or monitoring where, as has been noted by other working groups at this conference. FSMLs should conduct a survey of the resources and data available at each station and place the results online in a queryable format. The survey should include the basic features and attributes of all the stations, including geospatial information that describes their ecological settings. Interactive, map-based tools to access the kinds of data (surface soils, vegetation, etc.) that are being collected at each station would be valuable.

Next, it would be useful to know what ad hoc research or monitoring networks already exist within the consortium of FSMLs. With which agencies, non-profits, and private land managers are individual FSMLs collaborating? Which FSMLs already work with each other? A formal FSML network could build upon these grassroots efforts and accomplish a lot without significant new investments. It would also be useful to think about how to extend interpersonal social networks to broader geographic areas. These networks can, for example, help determine the best ways of managing biological invasions or protecting native species within a given region.

One of the barriers to successful networking has been resistance to data sharing. This is partly cultural, and may be starting to change, as younger scientists share data more readily. It is also partly logistical. Even those who are required to make their data available, as federal scientists are, may balk at the complexity of the standards and forms. FSMLs need to explore incentives to encourage partners in this venture to develop and contribute the necessary metadata and ultimately make the underlying data available. If the consortium can obtain grants to modernize its information systems and create true networks, that would be of great benefit to partner FSMLs. The Global Lake Ecological Observatory Network (GLEON), an international grassroots network of limnologists, ecologists, information technology experts, and engineers with a common goal of building a scalable, persistent network of lake observatories, is a great example of a success story.

<u>Communication between FSMLs and resource managers</u>

More cross-talk between FSMLs and resource managers would benefit both parties. Just as much as resource managers need scientific input for decision-making, FSMLs need to frame what they do in ways that maximize their benefit to society. Feedback from managers could help guide research priorities.

With some exceptions (such as Hubbard Brook Experimental Forest, U.S. Fish and Wildlife in the Florida Everglades, and the White Mountain Research Station in California), federal agencies likely do not go to FSMLs with their questions. That is probably partly because land managers are unaware of the activities at FSMLs, and partly because FSMLs are unaware of the needs of managers. Better communication is needed in both directions. This could be extended to industry, as well.

Regional collaborations have considerable potential and thus are very important. Most FSMLs are responsible for the land on which they are located, so they can conduct monitoring and research using manipulations that are not possible for researchers who are working on other lands (e.g., private land or protected lands). This is a significant advantage that expands the scope of monitoring and research that can be conducted, and could be of significant value to others managing land in the vicinity of the field station. The discussion group recommended a structured effort to involve FSMLs with resource managers, bringing together people with common interests using ecoregions or watersheds as a geographic organizing framework.

Conclusion

Workshop participants gravitated towards a few central ideas in plenary sessions and mashups as well as in individual working groups. There was a lot of excitement, first, around the idea of a network center. Marine labs and field stations serve their own areas well, but rarely interact with one another. The opportunity to integrate research and resources across marine, aquatic, and terrestrial boundaries could push science forward. The ability to share knowledge across stations could increase efficiency. A central office to coordinate standardized data collection and facilitate collaboration, as proposed by the Organismal and Population Biology working group, would allow research across ecological gradients, landscapes, ecoregions, and the continent.

The second point of near-consensus was the value of archiving legacy data. The shoeboxes, file cabinets, and field notebooks filled with data acquired by generations of scientists are the last stable reference point in a rapidly changing world. Preserving these—ideally, making them accessible and easily queried online—would allow research that can look back in time.

To begin to approach these large spatial- and temporal-scale questions, the network would need to know who is doing what where—a fundamental building block that requires surveys and databases, incentives for FSMLs and investigators to contribute data and information, and strategies for managing the data they contribute. Improved geospatial tools could be the glue that holds various data streams together both within and between FSMLs.

Finally, a sustainability perspective motivated the discussions of several of the groups. Stewarding the environment well enough that it can sustainably support the needs of the growing human population is the goal; achieving it will require a shift in the framework of environmental science. We are beginning to hone our questions and our tools for the job.

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Appendix C. Agenda

Building the Field Stations and Marine Laboratories of the Future: A Workshop Hosted by the National Association of Marine Laboratories and the Organization of Biological Field Stations. El Pomar Foundation Penrose House, Colorado Springs, Colorado, November 17 and 18, 2011

Thursday, November 17

7:30 Steering Committee and Working Group Chairs breakfast

8:15 Coffee at Penrose House

9:00 Welcome (Ian Billick and Ivar Babb)
Introductions of Working Group Chairs and Steering Committee members
Objectives of strategic planning
Deliverables
General approach for achieving workshop objectives

9:20 Trends in Science (David Schimel)

9:40 Aquatic Ecosystems as Sentinels of Change (Craig Williamson)

9:45 USFS Strategic Planning for the Experimental Forest Network (Peter Stine)

9:55 Introduction to Resource Management as Cross-Cutting Theme (Peter Stine)
- Prompts for consideration
- Deliverables

10:05 Introduction to Education as Cross-Cutting Theme (Kathleen Weathers)
- Prompts for consideration
- Deliverables

10:15 Break

10:30 Working Group break-outs
- Introductions
- Review deliverables
- Review critical discussion items
- Initiate discussions

Noon Lunch
During this special "mix-it-up" lunch please sit at the table with the same color that you see on your name-tag

1:30 Break-outs into Working Group discussions

4:00 Working Groups recap to large group - each group 10 minutes

5:15 Vans depart to hotel

(Agenda continued on next page)

Friday, November 18

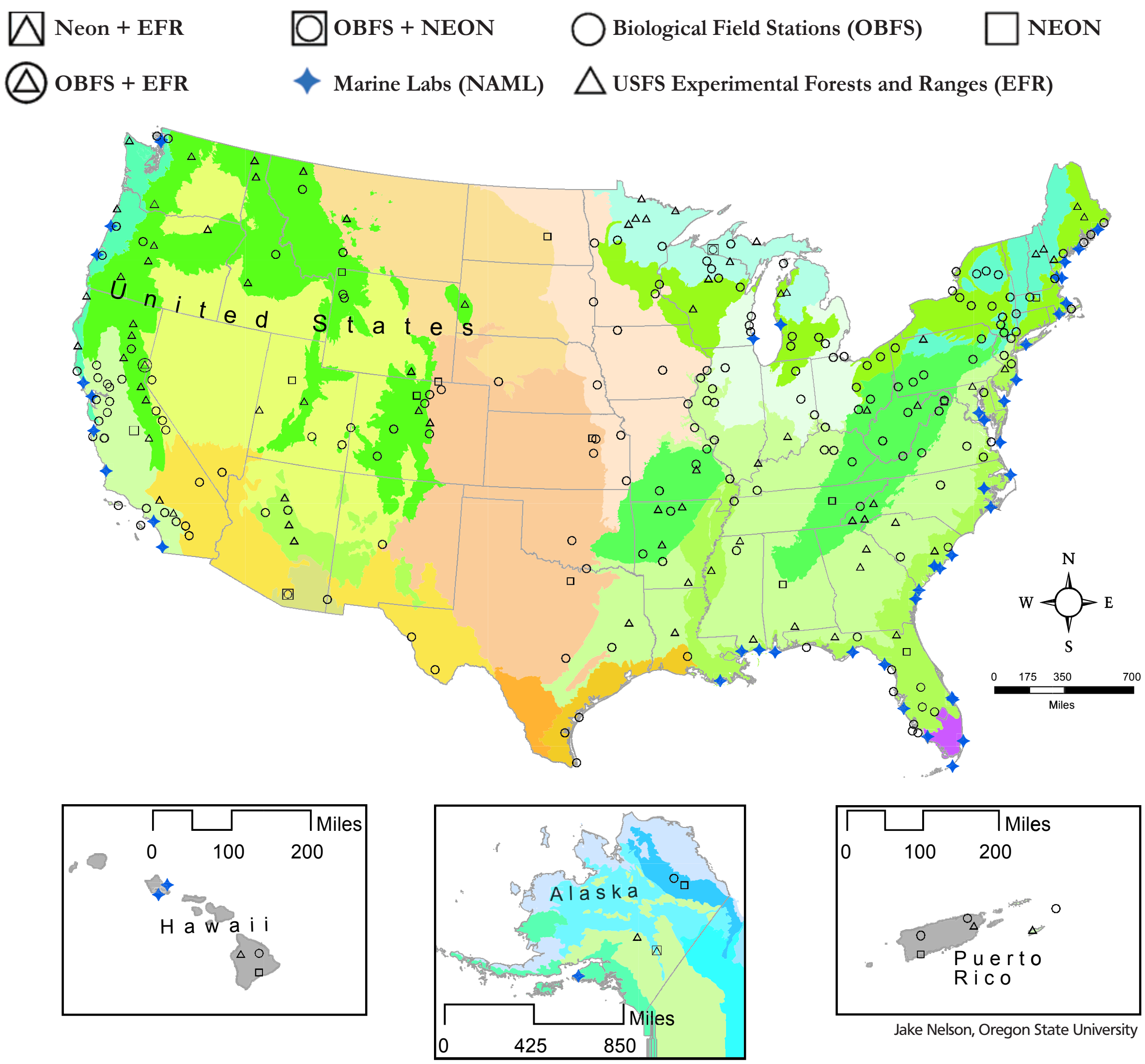
7:30	Steering Committee and Working Groups Chairs breakfast
8:15	Coffee at Penrose House
9:00	Working Group break-outs
10:00	Rotation #1: Working Groups meet in pairs
11:00	Rotation #2: Working Groups meet in pairs Members of Cross-Cutting Theme Groups split off into Education and Outreach Resource Management
Noon	Lunch Cross-Cutting Theme Groups may wish to continue discussions
1:00	Working Group break-outs - back to original rooms Prepare deliverables
4:00	Final presentation Logistics, thanks yous, reports Groups' discussion items
5:15	Shuttles depart to hotel

Saturday, November 19

7:00	Steering Committee and Working Groups Chairs breakfast
8:00	Steering Committee and Working Groups Chairs meet
11:00	End of meeting

Appendix D. Map

Field Stations and Marine Laboratories



Field stations and marine laboratories connect scientists to the environment all across the country and in every ecoregion. Shown here are some of the members of the Organization of Biological Field Stations and the National Association of Marine Labs; the USDA Forest Service Experimental Forests and Ranges; and core sites of the National Ecological Observatory Network.