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National Ecological Observatory Network: Beginnings, Programmatic and Scientific Challenges, and Ecological Forecasting

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2.1 Scientific and Programmatic Beginnings

In the United States and elsewhere, the development of large-scale scientific research infrastructure (RI) comes about from needs of the scientific community, as well as imperatives expressed in society and at high levels of government planning. In the 1990s, leaders in ecology began to express the need to address ecological theory at larger time and space domains and the need for large experiments that can elucidate unknown, nonlinear, or stochastic ecological behavior at a scale that could not be typically achieved within normal competitive grant cycles. Data were lacking to address these larger ecology "macrosystem" concepts (Soranno and Schimel 2014), and so the U.S. National Science Foundation (NSF) provided support to explore these notions of large-scale ecology. The idea of a large-scale ecological facility was novel and had never been done before, and the process to develop such a facility of this magnitude was a new challenge for the ecological community.

In fact, the NSF has a history of funding large-scale facilities and infrastructure projects, most notably telescopes, ocean-going vessels, and large geodetic arrays that are designed for multiple user groups and able to address a wide range of scientific questions. This type of support (from the Major Research Equipment and Facilities Construction, MREFC) is quite rare with only a handful of such projects funded every decade. While prominent members of the ecological community articulated the need for a large-scale facility, no one quite knew what it would look like. Some may say that NSF's initial design and development for a large-scale ecological facility was bold, visionary, and risky, because they too recognized its importance, yet did not know what "it" was. And so, NSF funded numerous planning workshops and white papers to clarify the vision of the science that an ecological facility could address as well as to begin defining its overall science scope in response to grand challenge questions. This process of scoping remains to this day very rich in scientific creativity (NSF 2002a–c), and it energized and engendered broad sections of the ecological community (Peters et al. 2008, Robertson 2008, Schimel and Keller 2015).

The deep well of ecological thinking that was brought to bear, in part, from the Long Term Ecological Research network (LTER), which is also funded by NSF, as well as other federally supported activities, for example, U.S. Department of Agriculture (USDA) Agricultural Research Service's Long Term Agroecosystem Research (LTAR), Department of Energy AmeriFlux, U.S. National Oceanic Atmospheric Administration's (NOAA) U.S. Climate Reference Network, and U.S. Geological Survey Earth Resources Observation System (EROS). NSF support for LTER provides a coordinating office, centralized data management, and core operational support at each of the ~23 sites distributed across the United States (with the exception of Palmer Station and McMurdo Dry Valleys of Antarctica and Moorea in Tahiti). And while there may be some science cohesivity and common general themes of research at particular LTER sites, the actual hypothesis-driven research is conducted by principle investigators (PIs) through federal peer-reviewed programs along typical 3-year funding cycles. Governance of LTER can be described as being layered with more complexity since its inception in 1980, and with a hub-and-spoke model, where a Network Science Council (the hub) that is very responsive to the changing needs of the science community, the PIs and site management (the spokes) (www.lternet.edu/node/140/). This structure fosters strong scientific creativity and adaptability (Table 2.1), and in the eye of the science community, scientific creativity trumps all.

When the ecological community was confronted with building a large ecological infrastructure, naturally everyone initially gravitated toward existing organizational models, for example, LTER, DOE AmeriFlux.

TABLE 2.1

Comparison of Programmatic Attributes between a Scientist's Approach (Often Networks) and a System Engineering Approach (Often Large-Scale RIs)

Scientist's Approach		System Engineering Approach	
Programmatic Attributes	**Pro/Con**	**Pro/Con**	**Programmatic Attributes**
Strong in scientific creativity	Pro	Con	Constrains scientific creativity to deliver the RI
Comfort-level for scientists and bottom-up approaches	Pro	Pro	New roles for scientists internal and external to the RI
Complexity becomes an open-ended problem	Con	Pro	Complexity is inherently planned for
Governance is often complex and not extensible	Con	Pro	Governance is inherently planned for, albeit complex
Changing scope, budget, and risk	Pro/Con	Pro	Clearly defines scope, budget, schedule, and risks
Difficult planning for program sponsors	Con	Pro	Develops planning horizons for program sponsors
Problematic for long-term sustainability	Con	Pro	Fosters long-term sustainability and operational models
Does not provide a unique solution for infrastructure design	Pro/Con	Pro/Con	Does not provide a unique solution for infrastructure design

Numerous vision and scoping studies were commissioned (e.g., NSF 2000a–c, 2002a–e, AIBS 2004a–f, and see www.neoninc.org/about/history). The vision and planning activities that NSF supported created a hyper-democratic community where (generally speaking) everyone involved thought that their designs, their concepts, and their areas of study were going to be used in the national facility design. Decadal planning for LTER envisioned more of a national infrastructure like that found in the National Ecological Observatory Network (NEON, more below) than how it is manifested today (LTER 1989). So on the one hand, the large interest in macrosystem-scale ecology demonstrated the scientific imperative for a national ecological facility. On the other hand, having this effort being perceived as everything to everyone created other problems. Expectations of bottom-up governance and with everyone's opinion being considered created difficulties in forming a management structure and defining the scientific scope (rf. Table 2.1). In attempts to include everyone's concept with the design, unrealistic early budgets of the NEON exceeded $1.7 billion for construction alone.

At this point, it is important to reinforce that prior to these efforts, building a large-scale ecological facility was unchartered territory and "near-death" experiences were commonplace in building other large-scale science facilities, such as telescopes, ocean research vessels, and particle accelerators

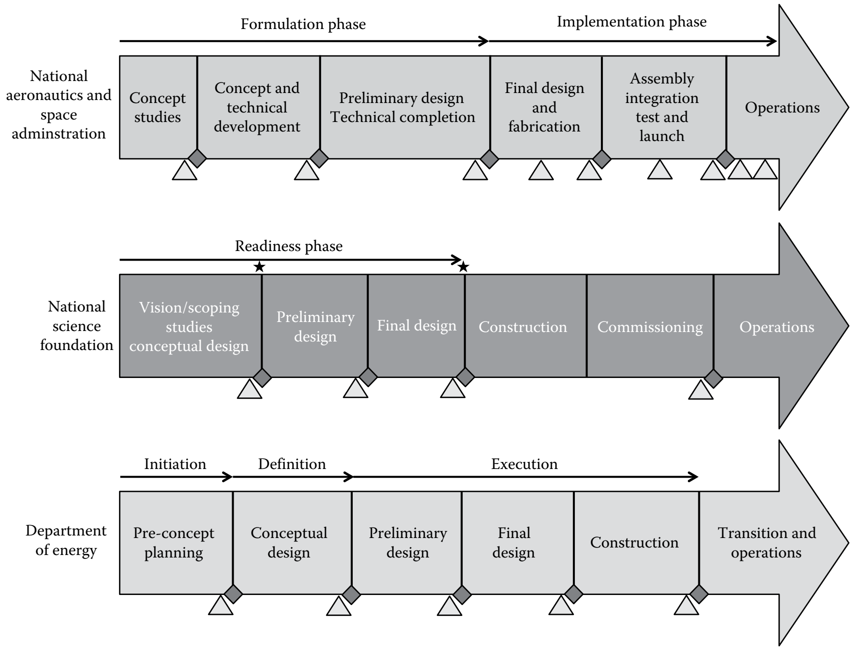

FIGURE 2.1
Conceptual diagram depicting the similarity of project development for large-scale science facilities by the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the Department of Energy (DOE). Triangles are formal reviews; diamonds signify a post-review decision, often "go/no-go." Each review and decision has specific purpose and name. Decisions transition the project development from one stage to another. Mid-process reviews are often capabilities- or readiness-type reviews.

(A. Beasley, pers comm). There is a common and very rigorous project development cycle used for building large-scale science facilities in federal agencies, for example, Figure 2.1, and other intergovernmental efforts, for example, the Large Hadron Collider. Developing the management ability and the means to bring the scientific community along in how to balance scientific creativity while also establishing a constrained ("baselined") infrastructure is necessary for the success of the facility. This is not an easy task, because it inherently involves changes in culture that can appear to challenge personal philosophies of how the best science is done. Indeed, we see this same issue play out in the development of many other ecological observatories, such as Australia's Terrestrial Ecosystem Research Network, the European Union (EU) Integrated Carbon Observatory System, and the EU Analysis of Experimentation on Ecosystems (AnaEE). In NEON's case, the persistence of key visionary members of the science community was also instrumental in bringing along (small) cultural shifts in approach and maintaining the momentum of project execution.

2.2 Societal Imperatives

Over the past decades, there has been increasing awareness by the public, scientists, and political decision-makers of the need for scientifically valid information to address the rapid pace of global environmental changes. Natural, managed, and socioeconomic systems are subject to complex interacting stresses that play out over extended periods of time and space (NRC 2007, USGCRP 2013, Becknell et al. 2015). Some are rapid and visible, like extreme precipitation, temperature, wind, and wildfire events, while others are subtle and play out over decades, like chronic nitrogen inputs changing ecosystem composition (McDonnell et al. 2014). These societal issues highlight the need for long-term data sets for understanding the context of scientific observations and for forecasting future environmental conditions or cause and effect interactions. Attempts to collate current long-term data sets have been largely accomplished through ad hoc integration of data from existing observation programs that were designed for other purposes (e.g., hypothesis testing), and that also fare poorly when judged against the rubric of being able to broadly address societal problems (Heinz 2006, 2008, Schimel et al. 2008). This lack of integrated, consistent, long-term data to address these societal questions has also been recognized by others (NRC 2011a,b, IOM 2013).

In 2001, the U.S. National Academy of Science (NAS) recognized the need to define the challenges that face society and science in addressing our changing environment (NRC 2001). This study brought together top ecological thinkers of the day and coalesced the societal imperatives as well as the scientific gaps in our understanding into one planning document (NRC 2001). They identified seven Grand Challenge areas of research and cast them into a cause (drivers/controls) and effect (processes/function) paradigm, where the drivers of change are climate change, land-use change, and invasive species and the effects play out in the ecological processes of biodiversity, biogeochemistry, ecohydrology, and infectious disease. This report served as the first "Decadal Survey" for the environmental sciences, and never before had such a robust (top-down) ecological planning document been developed. Recently, these Grand Challenges were reexamined, and it was determined they are as relevant today as they were in 2001 (Loescher et al. 2016). Hence, Grand Challenge approach has become one of the stalwarts in planning large-scale environmental programs and projects, and decades later, is still being used and validated today.

In 2003, the U.S. NAS conducted a second seminal report that contributed toward the evolution of the National Ecological Observatory Network (NEON). Here, the NAS (through the National Research Council [NRC]) advocated for observations and experiments to be made consistently across the North American continent and creating the needed long-term, decadal-scale ecological data sets. While the NAS report did not specifically define science scope, it did contribute toward the discourse of what could be observed at continental scales. Programmatically, this report also raised NEON's mantel to be more broadly considered by the National Science Board (NSB). The NSB has several functions key to NEON's development it (1) aligns the policies of NSF within the framework of national policies set forth by the President and the Congress, (2) identifies issues that are critical to NSF's future, and (3) has NSF budgetary oversight. This is mentioned here because the process to acquire support for such a large-scale endeavor has bearing on how the science is manifested into the final designs and realized in operations.

As part of NEON planning effort in 2006, prominent members of the ecological community again came together and crafted NEON's Integrated Science and Education Plan (ISEP). This linked the ideas of Grand Challenge areas articulated by the 2001 NRC report with the need for a continental-scale observatory outlined in the 2003 NRC report, to formulate NEON Grand Challenge questions:

- How will ecosystems and their components respond to changes in natural- and human-induced forcings such as climate, land use, and invasive species across a range of spatial and temporal scales? And what is the pace and pattern of the responses?
- How do the internal responses and feedbacks of biogeochemistry, biodiversity, ecohydrology, and biotic structure and function interact with changes in climate, land use, and invasive species? And how do these feedbacks vary with ecological context and spatial and temporal scales?

Within these questions, we see the cause and effect paradigm expressed and the need to scale across space and time. These concepts have been slightly refined in Schimel et al. (2011), but the essence of the ISEP still remains in NEON's designs today.

The national relevance and timeliness of NEON's design continued to resonate with other societal imperatives over the course of its development. PCAST (2011) recognized that these changes in ecosystems threaten to erode the nation's (U.S.) environmental capital, resulting in disruptions of these services that would likely alter the fundamental trajectory of society and quality of life manifested across the United States and over large parts of the world (PCAST 2011, Schimel et al. 2011, NRC 2011a). Moreover, the "Fragmented federal investment in monitoring ecological change weakens national priorities" (PCAST 2011). The National Plan for Civil Earth Observations (Holdren et al. 2014) outlined specific Federal actions to "… address the threats to both the environmental and the economic aspects of well-being that derive from the accelerating degradation of the environmental capital." In brief, they call for (1) the continuity of sustained observations for earth system research, which includes the establishment and maintenance of programs to ensure data continuity for high-impact sustained research observations; (2) continued investment in experimental observations, which includes continuing to invest in research and development, incorporating technological advances to improve observations; (3) planned improvements to sustain observation networks and surveys for all observation categories, that is, proceeding with planned improvements to sustain observation systems; and (4) the continuity of, and improvements to, a rigorous assessment and prioritization process. This plan includes a national-level process to prioritize sustained observations for both research and public services and for experimental observations, and includes a process for external advisory input and strategic balance.

These challenges remain today, and from the top-down, the NSB aligns these national priorities with the NSFs policies. NEON as presently designed meets all these national priorities. In addition, NEON expands its scientific footprint through federal agency partnerships and leverages the federal investments in NEON and other agency programs to enhance its overall impact, and continues to be responsive to the changing environmental societal imperatives.

2.3 Hypotheses to Requirements

Often asked when discussing someone's science is "what is your question?" or "what are your hypotheses?" Building a large-scale scientific facility poses a slightly different scenario, where the facility has to be able to address a myriad of hypotheses relevant now, and in the future and at multiple scales. Lacking a crystal ball, the programmatic task then lies with how do we best design a facility that can broadly accommodate the ecological community and still be able to address specific research questions now and as they change in the future. A second (and related) programmatic challenge is how to determine the scientific scope of the facility to such an exacting degree as to be able to estimate (fix) its construction and operational costs, schedule, staffing and staffing needs, institutional support functions, and manage risk. These challenges are very foreign to an ecologist.

System engineering provides unique tools to distill questions and hypotheses into requirements. In turn, having requirements defines what needs to be built to meet the scientific needs and also the fidelity needed to constrain cost, schedule, and risk. Take, for example, the null hypothesis: ecosystem-scale litterfall rates are not controlled by the community of overstory tree species. An investigator may address this hypothesis by estimating the tree diversity by area and describe life histories, place a number of litterfall traps in randomly distributed plots, collect monthly sample, and analyze accordingly, etc. A system engineering approach may include determining a priori what is the expected spatial and temporal signal/noise ratio of the phenomena to be tested, in this case, litterfall and overstory tree diversity, estimate the scale of statistical independence, and craft the science requirements something like (Shishko 1995, Kossiakoff et al. 2011):

- Litterfall traps shall be 1 m × 1 m horizontally square and have a perimeter edge along the top that is 7 mm in width.
- Litterfall traps shall be mounted 0.5 m above mean ground level.
- Litterfall traps shall collect leaves and biotic debris, and not hold water.
- Litterfall traps shall have a minimum of 5 L capacity.
- Litterfall traps shall be placed at least one statistically independent scale length from the next trap.
- The number of litterfall traps shall have the capability of collecting 80% of the spatial mean on a biweekly basis (and so on).

Requirements are crafted so that they can be tested and verified with one testable feature per requirement. Requirements are then reviewed by independent, outside scientists to assure they meet community expectations and needs, and to assure the data are measured consistently over the life of the facility. A control process is put into place to version, test, and approve any changes, as it becomes onerous if a project continually changes its requirements. While this may seem tedious, it also provides the context to communicate the science to non-ecologist staff within NEON, such as site engineers deploying the field experiment, or cyber-infrastructure engineers coding the analytics. Developing requirements for a large science facility only works for scientific approaches that are broadly accepted by the community, or considered best community practices, like measuring tree diameter at breast height, that is, 1.37 m (4.5 ft) above ground. It does not work for approaches that may still be considered as experimental, for example, using a specific algorithm to use to estimate columnar CO_2 through the atmospheric boundary layer that will likely change in a few years. Whether a hypothesis is tested by an individual investigator or distilled into requirements and then tested, in either case, there is no single unique solution in how the experimental design is finally expressed and executed (Shishko 1995, Kossiakoff et al. 2011).

A key challenge in designing NEON was to provide a facility that brings scientific relevance to the largest possible group of ecologists today and in the future. So for a project the size of NEON, system engineering does not end at capturing the science requirements. The process started with the Grand Challenge questions that are meant to be provocative, embody scientific and societal imperative(s), and be quite open ended (see Figure 2.2). From there, the scientific community was asked what would be their hypotheses to address the Grand Challenge questions. Having thousands of hypotheses in hand, NEON staff scientists then asked what are the data products

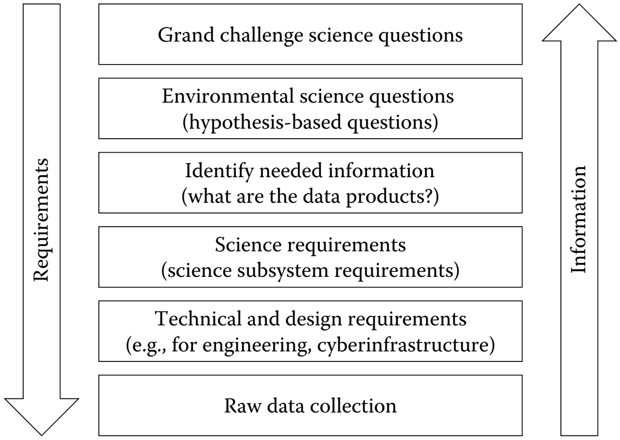

FIGURE 2.2
A simplified, scientist's view of the system engineering approach to distill Grand Challenges and hypotheses into tiered requirements and, conversely, how the flow of information can be used to address the Grand Challenge questions.

needed to test these focused research questions. From there, science requirements were drafted, which in turn could be used to capture technical and design requirements. The ability to assess the requirements at a very fine level of (system engineering) granularity also allows us to verify the data type, quality level, and quantity—the flow of information at the point of data capture, through the facility, in order to address the grand challenge questions (Figure 2.2). The progression to capture requirements and assess the type, quality, and flow of information was not a static process. NEON staff iteratively assesses each requirement and how it is manifested into the overall design, over and over, and often with many internal reviews and external advice. Once the requirements became fixed, the project became baselined and subsequently budgeted, scheduled, risks managed, and transitioned to operations. The capture of requirements is oversimplified here to illustrate the scientist's perspective. But ultimately, availability of this tsunami of data is the payoff to scientists.

Other key system engineering activities are the change control processes that manage these dynamic requirements, and the testing, verification, and commissioning processes that transition construction activities into operational. Many large-scale science facility projects attribute their success to being able to establish and maintain a creative tension between the science and engineering teams. For example, a scientist's choice for a specific sensor that meets the science requirements for accuracy and precision may place undue operational burden to manage that accuracy and precision across the range of environmental conditions found across the North American continent. In another example, there are "best community practices" for capturing small mammals in specific ecosystems, but extending the same protocols for small mammal capture across the continent remains challenging. Moreover, developing adaptive field sampling protocols to meet and manage expected mark-recapture signal:noise ratios also remains challenging. System engineering tools that distill the requirements of both the scientists and engineers craft balance, optimize and standardize the install, design, maintenance, operation, data capture of a particular ecological quantity while still meeting the scientists requirements. System engineering often provides the context to maintain this creative tension between scientists and engineers (Figure 2.3). But of course, one of the roles of leadership is also to ensure that all of the Project Teams are balanced and complementary in responsibilities and authority (and this also applies to Project Sponsors) (Jain and Triandis 1997, Hughes et al. 2014). This is difficult to manage through the course of the project given that the combination of scope, budget, schedule, risk, people management, and politics is inherently a nonlinear, multivariate problem, with some solutions from one project do not necessarily translate to another (A. Beasley, pers. comm.). That said, there are also different philosophies on how best to apply system engineering principles, and how and when to engage scientists. The National Aeronautics and Space Administration (NASA) model to build

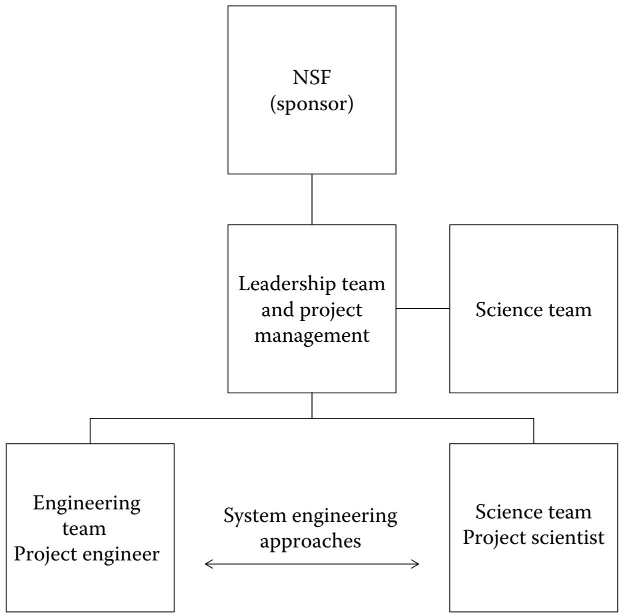

FIGURE 2.3
Simplified project management model to demonstrate the need for creative tension between science and engineering efforts, and the need to balance responsibilities and authority among the associated management strata (and this also applies to project sponsors). (This figure follows similar logic found in Schimel and Keller, 2015, Figure 3 therein.)

satellites involves bringing scientists together initially to capture the science requirements and again during the testing and verification stages. Requirements are often only captured when a design or scope decision needs to be made. This differs from the NSF or Department of Defense (DOD) model where requirements are determined at a very fine degree of fidelity before any construction is initiated. The consequence of this approach is that a longer time is needed than originally planned for, leading to cost overruns (in the case of DOD), or descoping science (in the case of NSF). In Europe, clearly strong system engineering principles were applied to many large-scale science facilities, that is, the Large Hadron Collider. Yet interestingly, the EU FP7 project ENVironmental Research Infrastructures (ENVRI) has taken a slightly different approach given the large plethora of environmental research projects that have been strategically initiated. A common reference model (roadmap process) is used to define cyber- and informatics functional structures that are common among all EU environmental research infrastructures (Chen et al. 2013, 2014, Chen and Hardisty 2014). This helps planning and prototyping activities, but also operational requirements and creates a structure to foster interoperability of data among these facilities. ENVRI Science and Technical reference models are forthcoming. In all cases and for all research infrastructures, managing scientific scope and scope creep is difficult, is an ongoing activity, and requires vigilance and effective programmatic structure, for example, system engineering approaches.

Building new environmental research facilities is still new programmatically and quite a foreign concept for some scientific communities, for example, what do the data mean for my science and how do I apply my science to build something that has never been done before. Each infrastructure is faced with a unique suite of programmatic issues and scientific challenges (otherwise they would be commonplace and formulaic to build). And at the same time, each type of system engineering approach has its strengths, shortcomings, and benefits that have to be weighed against a rigorous assessment of need and feasibility when constructing an infrastructure.

2.4 Unrealized Benefits of Requirements

Extracting requirements from hypotheses was originally based out of need. Requirement capture is a very robust tool to define scope, budget, risk, schedule, and transition to operations (in order to secure funding support) and is a means to communicate what is needed by the scientists to other project teams and nonscience experts, for example, engineer, permitting, or operational staff. Because in the case of ecology and NEON, this activity had never been done before, it is an untapped resource waiting to be exploited.

Requirements give us the basis to communicate the exact design externally as well. This is not to say that they can ever replace hypotheses, but it provides accurate details of exactly what is being constructed and delivered to the community—a consistent, continental, physical infrastructure and long-term, multiscaled data sets and data products that serve as a context for research and education (rf. www.neoninc.org/sites/default/files/basic-page-files/2015-03-23.SCA_.Report.pdf).

Two general categories of users have expressed interest in exploiting NEON requirements. One camp wishes to extract specific requirements to have a NEON-like infrastructure of their own, and a second group, typically other networks and observatories, wishes to link physical and informational infrastructures in an interoperable way to expand both NEONs and their capabilities. The users of first group are, in essence, developing NEON satellite sites, where they may extract protocols, whole or in part, such that they can collect data in the same way as NEON. Others wish to use NEON infrastructure designs in their entirety to augment the NEON's overall capability. For example, to utilize NEON's mosquito sample protocols at higher spatial density in areas where West Nile Virus prevalence is expected to increase, or to construct and operate a fully instrumented tower in an urban environment.

The second category of users is typically other networks, observatories, and infrastructures that wish to become interoperable with NEON. Interoperability is an emerging concept that can mean many different things to different people. Here, we broadly define it as all the efforts needed to enhance the use and transfer of data by removing the technical, scientific, cultural, and geopolitical barriers. Requirements provide us with the specific language to make this possible to a fine degree of fidelity. It is not meant to be prescriptive, rather a dynamic community-driven approach, in which many emerging groups use requirements as a backdrop to steer the forum for discourse (www.coopeus.com, www.esipfed.org, rd-alliance.org).

Interoperability, as defined for scientific utility, has four focus areas previously identified (Chen et al. 2008, Peters et al. 2014). First, why are the data collected in the first place? Identifying the questions, mission statements, hypotheses, or requirements creates the basis to understand the constraints, synergies, and gaps in the data to be shared. Second, is the epistemological question of how to trace the quantities measured to known international standards, first principles, or best community practices? As discussed earlier, it is important to develop uncertainty budgets. Third, how the algorithmic procedures are used to calculate a specific quantity may differ among research groups, networks, observatories, etc., for example, productivity measures? It is fine if one group measures net ecosystem exchange of carbon one way, and another group measures it differently. The important criterion is for the relative uncertainties across algorithmic approaches to be known and estimated, so that they can be used in comparative analyses and predictive Bayesian approaches (Reckhow 2003, Johnson and Omland 2004). This issue also applies to models or protocols at the high level of abstraction such as how to design a national forest inventory, a monitoring network, or a monitoring reporting and verification (MRV) system. And lastly, the issue is broadly defined as informatics. This includes the obvious, such as data and metadata formats and fields, for example, ISO 19115 compliant (www.iso.org/iso/). But it also includes issues of intellectual property rights, citation and attribution, persistent identifiers, open data policies and sovereignty, data portals and discovery tools, and controlled vocabularies. For example, there are conceptual barriers that include syntactic and semantic differences in information to be exchanged; one person's definition of litterfall may be quite different from another's, or how should one label a mashed up archival sample of mosquitos for DNA analyses? In the case of data sovereignty, this includes not only an individual country's rights to its data, but also the organizational barriers within a country that define the country's agency or ministry responsibility and authority over the data, and their mandates to share with other organization structures. This issue is evident in developing countries where the organizational responsibilities are usually not clearly defined, or managed, often hindering collaboration among actors. The degree to which data are truly interoperable is the degree to which these four elements are adopted by collaborative activities and facilities, which would not be possible without explicit requirements.

2.5 The Need and Philosophy of Ecological Forecasting

NEON's science strategy is complex and described in Schimel et al. (2011). NEON staff have taken the Grand Challenge questions, and through requirements capture, they have identified discipline-specific science teams to address specific ecological properties and processes to be measured. A scaling strategy from the site to the continent also was incorporated. At the site level, the science teams are: terrestrial instrumentation; terrestrial organismal sampling; mobile deployment (measurement) platforms; and aquatic instrumentation and organismal sampling (www.neoninc.org/science-design/spatiotemporal-design). NEON has 84 sites distributed across the United States from the north slope of Alaska to Puerto Rico, from Hawaii to New England. They are distributed according to our understanding of how to assess the trends in regional ecological properties and processes, and how the Grand Challenges manifest regionally. Site-based NEON ecology is centered on the ecosystem scale. Our scaling strategy includes aerial flyover of all our sites with an airborne observation platform (remote sensing aircraft) that includes visible imaging hyper-spectrometer and downward facing waveform and discrete LIDAR. These data can then be combined with satellite imagery or other federal data sets to scale ecological quantities from the site to region to continent. All the data are free and available to anyone through a data portal (data.neoninc.org/home), and data product catalogs can be found at data.neoninc.org/data-product-catalog.

Even though the capability of this observatory is profound, as with other continental-scale environmental observatories, for example, Australia's Terrestrial Ecosystem Research Network (TERN, www.tern.org.au), China's China Environmental Research Network, DOE AmeriFlux (ameriflux.lbl.gov), and others mentioned in this book, the scientific and societal imperatives to predict future environmental conditions and ecological functions remain (rf. Katz and Murphy 2005). Reenforcing this notion, Smith and Zeder (2013) suggest that the expectation for science to provide future guidance in the face of growing human population living with limited natural resources is a defining attribute in the Anthropocene. Interpreted another way, these observatories provide information, but that still has to be converted into knowledge and new understandings by the user community. As such, NEON has also been charged by the NSB to "… enable an ecological understanding and forecasting… by providing infrastructure." There are several challenges to meet this objective.

2.5.1 First Challenge

NEON had to define what is meant by "ecological forecasting." Here, we place the cause and effect paradigm into two problem statements (rf. Table 2.2):

1. What is the most likely future state of an ecological system?
2. To provide an applied context; what are possible future ecological outcomes if a given decision is made today?

TABLE 2.2

Ecological Attributes That Help Us Conceptualize How the Internal Ecosystem Structure and Function May Respond to Perturbations and/or Disturbances

Ecological Attributes	Brief Definition	Reference
Resilience	The capacity of an (eco)system to experience "perturbations" or "disturbance" while retaining essentially the same function, structure, feedbacks, and identity	Holling (1973)
Adaptability	The capacity of the (eco)system to manage its internal resilience, this can include all the internal functions, structure, etc., or some in part	Berkes et al. (2003)
Transformability	The capacity to move an (eco)system from existing system cannot maintain itself due to a "perturbation" to a new fundamental (eco) system state	Chapin et al. (2009)

2.5.2 Second Challenge

Ecosystems are continually subject to changing conditions (abiotic environment) and also subject to natural and man-made disturbances (Becknell et al. 2015). These disturbances traditionally have been viewed as episodic, regional, and punctuated and stochastic in time (Dale et al. 2001), for example, ice, snow, and wind storms, fire (made-man and natural), drought, hot spells, earthquakes, volcanic activity, and clear-cutting of forests. Such disturbances affect the ecosystem structure, functions, and process rates (Smith et al. 2009), such as nutrient availability, succession, and broken physical structure. Chapin et al. (2009, Box 1.2) elegantly describe the susceptibility or resistance to change that ecosystems may experience in the presence of disturbance, contributing to the ideas of resilience and adaptability (rf. Table 2.2). But in today's global environment with continual and increase in inputs of reactive nitrogen, and increases in temperature, CO_2, CH_4, atmospheric aerosols, invasive species, land-use change, are a chronic sources of disturbance, the presence or rate of which have not been experienced by ecosystems (Smith et al. 2009). Under these conditions, ecologists do not know how plastic ecosystem functions are (adaptability, Table 2.2), will they transition to different states (transformability, Table 2.2), can redistribute to more favorable environments (Iverson and MacKenzie 2013, Zolkos et al. 2015), or how/if natural selection plays a role (Quintero and Wiens 2012, Thorpe et al. 2015). What ecologists know about ecosystem functions today may not be (if not likely) how they will behave in the future. Being able to understand a posteriori how and why ecosystem states change in response to a given event falls short in being able to deliver on addressing our societal imperatives (NRC 2003). Hence, these theoretical underpinnings provide a context for how these systems may interact, but there is a lack of data to test new theories (Collins et al. 2012), and to provide the context to quantitatively predict future ecological states as an operational function of an observatory.

2.5.3 Third Challenge

How can a prognostic capability be designed when the future temporal and spatial signal/noise ratio of ecological processes is expected to change? Moreover, there are many processes, which express nonlinear and stochastic behavior. For example, temperature tipping points (Wall 2007, Laurance et al. 2011), susceptibility to droughts, and stochastic changes in functions from chronic nutrient inputs, as in the case of the Kuparuk River, AK (Slavik et al. 2004, Benstead et al. 2005). We can only design according to what we know about process-level temporal and spatial signal/noise ratio today. Even though no one has designed a large-scale ecologic observatory with a mandate for forecast ecology before, it is necessary, however, to embody

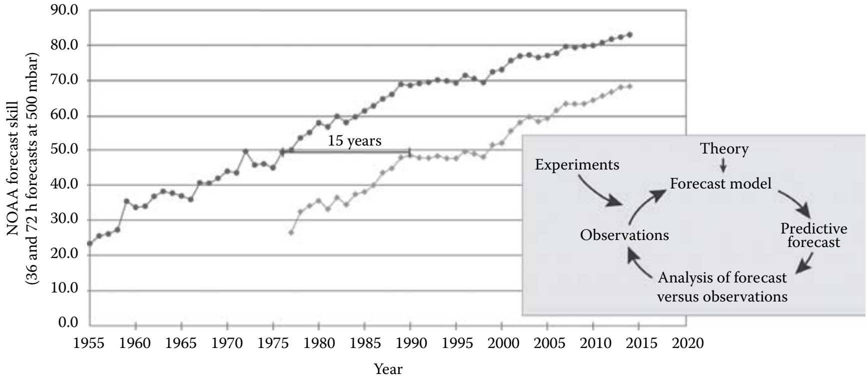

FIGURE 2.4
U.S. National Oceanic Atmospheric Administration's (NOAA) forecast skill from 1955 to date. Forecast skill is for the atmospheric 500 mbar pressure isopleths that control the continental-scale synoptic weather patterns more than 36 hour (dark gray trace) and 72 hour (light gray trace) periods. Note the 15-year lag in the level of forecast skill between 36 and 72 hours, while the rate of improvement (slope) is essentially the same. Data redrawn from www.nco.ncep.noaa.gov/sib/verification/s1_scores/s1_scores.pdf. Inset is the iterative concept of theory, forecast, analysis of observations, and experiments, to advance forecast skill.

a philosophy where new understanding can be accommodated into the designs, measurement suite, and forecast ability.

The philosophy that NEON embodies to forecast ecology mirrors the NOAA's strategy for improving weather forecasts, that is, for the 500 mbar (that controls the continental-scale synoptic weather patterns) more than 36 and 72 hour forecasts (Figure 2.4). Accuracy in NOAA weather forecasts improved almost linearly from 1955 to date, from 20% to more than 80% today. There was no large increase in skill with the deployment of >3000 new weather stations in the 1960s, no increase in skill with weather satellites in the 1970s, and no increase with new supercomputers (particularly in the 1980s and 1990s). Instead, the increase in forecast skill was achieved by starting with theory, constructing theory-informed forecast models, and challenging the model forecasts with observations and improvements in models that, in turn, inform new types of observations and/or capabilities to challenge theory again. It is this iterative approach that enhanced the NOAA forecast skill, and this philosophy is used by NEON to approach how we can forecast ecology.

The ability to incorporate nonlinear behavior, such as tipping points, is still missing within NOAA's forecasting approach. This is the core rationale to include the role of large-scale ecological experiments into continental-scale research infrastructure, such as NEON and AnaEE, to be able to elucidate unknown processes and nonlinear responses. Bringing it all together, the role of an observatory to forecast ecology is to provide (1) estimates of ecosystem state(s), (2) estimates of key ecological state variables and parameters,

(3) experiments to elucidate unknown processes and nonlinear responses, (4) observations collected consistently and systematically over time and space to challenge iterative forecasts, and (5) the ability to augment the infrastructure to improve iterative forecasts. Bringing this philosophy to bear is a new paradigm for ecological research.

2.5.4 Fourth Challenge

The field of continental-scale or macrosystem ecology is still quite nascent (Heffernan et al. 2014). Current ecological theories have to be applied to the new macrosystem context, as well as the very real opportunity for new macrosystem theories to emerge. Clearly, addressing this challenge is a key to inform the iterative forecasting philosophy outlined in Challenge 3. Panarchy may be a leading macrosystem theory (Gunderson and Holling 2002), but deriving testable hypotheses remains a challenge. Many important studies tackle the complex concepts of resiliency, adaptability, and transformability (rf. Table 2.2). But hypotheses and results are all too often specific to an ecological subdiscipline, time period or space domain, and/or use case with little ability to apply these findings to other systems or find new system behavior a posteriori with little prognostic capability. Conversely, some prognostic models exist but lack the long-term, consistent, multiscaled data sets required to distinguish among alternate hypotheses or to assess performance among models (Schimel et al. 2011). Lastly, the current overuse of correlative statistics will not be sufficient when more mechanistic understandings are needed for prognostic applications (rf. Collins et al. 2010).

Again, NEON and other research facilities are charged to "enable an ecological forecasting," which means providing the data needed to forecast the future state of an ecosystem and to have the ability to augment the infrastructure to accommodate the future needs of ecological science. Ecological forecasting will not work without the close, collaborative working relationship among scientists, NEON (observatory) scientists, and sponsors. Meeting this challenge is the primary charge to the ecological community to confront (new) theory and develop new statistical approaches to advance our prognostic understanding.

2.5.5 Fifth Challenge

Our ability to communicate results of ecological forecasts has to be improved in order to have broad utility across sectors of society. This is everyone's responsibility: scientists, decision-makers, and the public, alike. Ecological forecasting should not attempt to provide a single "answer" to a question or be touted as a panacea. Rather, forecasts should provide a range of possible or likely outcomes or provide a trend analysis—an expected trajectory of an ecological process. In this way, a "decision space," or in engineering terms a "trade space," can bound or constrain a particular problem. Uncertainties should also be reported along with these analyses.

Reporting uncertainties goes hand-in-hand with the data in terms of informing how the data can be interpreted and how they are used, which delves into the realm of human behavior. When wishing to make science data applicable to decision-makers, interpreting uncertainties often equates to decisions based around risk. Uncertainties and risk management mean different things to scientists than to decision-makers and the public. Take, for example, the Intergovernmental Panel on Climate Change report (IPCC 2013) where the forecasting results have led scientists to refine their estimates, while convincing federal and state governments to initiate planning for food and water security, leaving average citizen disenfranchised in their own personal decision-making process by long 50–150-year forecasts, for example, why should I change my behavior if the risk may or may not hit in 100 years? New dialog and new paradigms have to be explored to make the communication of forecast results more understandable, meaningful, and actionable along all strata of society.

2.6 Future Expectations

Community engagement between the future users and NEON staff is challenging while building the observatory due to several competing pressures. Queries from future users stem from a genuine, sincere, and strong desire to understand what NEON (or other infrastructure) can provide to advance (their) science and education, what is new and exciting in the observatory design that is at the science frontier, and how they can contribute. Staff scientists are faced with applying their academic skillsets toward designing and building something that has never been done before, for example, the old paradigm of trying to building the plane while at the same time trying to fly it. At the same time, staff scientists are faced with an unfamiliar organizational structure of NEON that acts as a construction company, scientific institution, and a start-up company combined, each with its own culture, that often manifest in needs to build internal organizational function/structures for one culture. Compounding this dynamic, are the rapidly changing institutional needs, and the changing and unforeseen reporting and oversight of the sponsors themselves. The need to engage with the user community has never been greater and, at the same time, always outweighs the institutional capability to do so. This is not meant as an excuse, but rather a common, reoccurring reality seen by all research infrastructure during their construction.

Often, institutional structures are developed to foster broader engagement, such as technical working groups, advisory boards, workshops, and ad hoc position papers. While useful, they tend to be targeted efforts, or viewed by the community as having limited impact. Given the combination of culture change, the need to build institutional capacity, and the very large effort needed to report overall progress in building the infrastructure to the sponsor (i.e., NSF), it is unrealistic to think that the ability to broadly engage with future users will change in the short term (5–10 years), but rather it occurs slowly and incremental over long operational timescales, for example, decades.

Transitioning into operations (OPS) presents additional programmatic and funding challenges. Transitioning from construction to OPS is also part of a common development process (Figure 2.1). A different set of skills is needed for operations than construction. For example, the large number of PhD-level scientists needed to apply their intellectual capital for design and to assure the design has been constructed correctly, is different from the skill levels needed to execute field protocols and quality control the data. This will also mean transitioning all the ongoing relationships among the external user community, advisory groups, and staff scientists to meet the changing needs of OPS. Because workflows and protocols will be further tested and hardened during OPS, there will be a natural tendency to refine and optimize them. There will also be a natural tendency for sponsors to also require the optimization of workflows and protocols. Hence, system engineering approaches (discussed earlier) will be more than ever required during OPS to assure that the optimizations will not compromise the science being delivered.

Large federal investments in research infrastructure are often funded by "new" money, as in the case with NEON's construction funded through the MREFC program. While there may be some "new" monies being successfully secured in new annual federal budgets for an OPS budget, the majority comes from existing budgets, as in the case of the NEON OPS budget coming from the "Research and Related Activities" (R + RA) general account of the BIO Directorate at NSF. OPS budgetary decisions become a matter of balancing a portfolio of competing programs with very likely new programs emerging to directly support the science being delivered by the new research infrastructure. This is why OPS budgets are often viewed as a zero-sum game. Similarly, in Europe and elsewhere, the majority of OPS budgets for distributed research infrastructures come from budgets within member countries, each with their own political and scientific agenda, and different funding schedules. So within NSF or EU member countries, securing consistent long-term support for important environmental observations and experiments becomes a political discourse and trade-off on budgets from competing programs with very little input from the user community—and why we can expect in all circumstances to have downward pressure applied by sponsors to optimize OPS workflows and budgets. For example, the NSF MREFC construction award to NEON comes with formal assurances to support OPS, but the flow of funding has to be in the President's Budget, appropriated by Congress, transferred to NSF, and subject to internal NSF budget discussions. On the other hand, an EU infrastructure such as the Integrated Carbon Observing System (ICOS, www.icos-ri.eu) is distributed across European countries under a novel legal framework: European Research Infrastructure Consortium (ERIC). There is core ICOS OPS funding by the European Commission, but the majority of the OPS support comes from member countries, each with different National Budget cycles and priorities.

The Gartner hype cycle for technical development can be directly applied to building research infrastructures, Figure 2.5 (rf. Jarvenpaa and Makinen 2008). At the beginning, when the new concepts were being forged into the NEON design and there was broad adoption of the user community, NEON was touted as being everything to everyone (Section 2.1). Clearly, this cannot be the case and expectations were inflated. During the very difficult time of building the intellectual capital needed to design and construct NEON and faced with a tsunami of urgent tasks and reporting requirements, NEON staff were disillusioned and compromises were made. Now with NEON and similar environmental research infrastructure being close to OPS; hopefully the community has seen past inflated expectations, staff has rallied, and while the overall science capability is not what it could be, but at the same time, it is balanced with a realistic operational ability. It is also important to note that NEON was designed based on the understanding of the needs and technologies at that time with the goal of being able

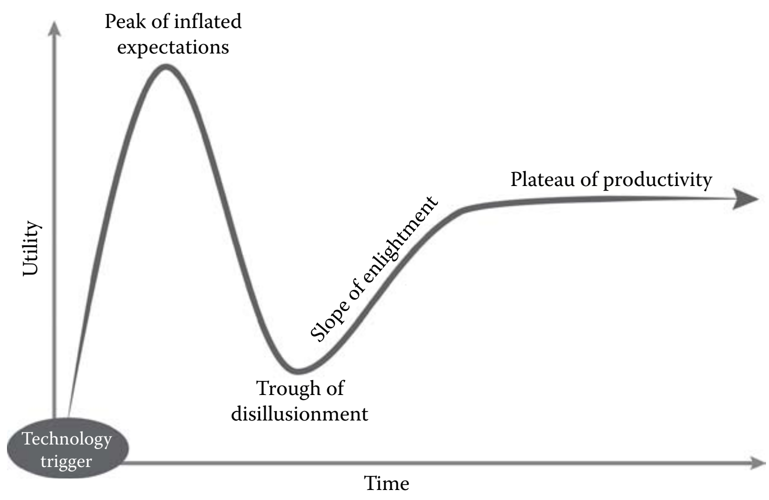

FIGURE 2.5
The abbreviated Gartner hype cycle of development.

to provide the data for ecological forecasting. It is not possible to imagine all the ways that NEON data will be used in the future, and as in the case with many large-scale federal investments in research infrastructure, the most profound discoveries are likely to be those not originally intended. The Gartner hype cycle helps communicate the development process and expectations of future science capability to scientists, decision-makers, and the public alike.

In conclusion, the success of NEON and other research infrastructures will be in how they are used, but also how well they are viewed in the constellation of all other federal (agency) programs, global initiatives, and private enterprises. Because its annual OPS budgets are subject to political (non-linear) processes to determine funding rates, its scientific utility will also be judged in how well it can contribute to and interface with other Federal, private, and international programs, that is, USGS EROS, North American Carbon Program, USDA LTAR, DOE Atmospheric Radiation Measurement, National Aeronautics and Space Administration ROSES, NOAA Earth System Research Laboratory, and globally with Arctic Council, Group on Earth Observations, Future Earth, CoopEUS, etc. There are similar analogs with other environmental research observatories. This calls for a concerted effort in establishing and aligning efforts among these stakeholders. And even though the dovetailing with other programs was not inherently planned for, it does become part of the political discourse, funding for OPS, and metrics for success.

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