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SHORT COMMUNICATION

Lessons from constructing and operating the national ecological observatory network

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The United States (US) National Science Foundation's (NSF's) National Ecological Observatory Network (NEON) is a continental-scale observation facility, constructed and operated by Battelle, that collects long-term ecological data to better understand and forecast how US ecosystems are changing. All data and samples are collected using standardized methods at 81 field sites across the US and are freely and openly available through the NEON data portal, application programming interface (API), and the NEON Biorepository. NSF led a decade-long design process with the research community, including numerous workshops to inform the key features of NEON, culminating in a formal final design review with an expert panel in 2009. The NEON construction phase began in 2012 and was completed in May 2019, when the observatory began the full operations phase. Full operations are defined as all 81 NEON sites completely built and fully operational, with data being collected using instrumented and observational methods. The intent of the NSF is for NEON operations to continue over a 30-year period. Each challenge encountered, problem solved, and risk realized on NEON offers up lessons learned for constructing and operating distributed ecological data collection infrastructure and data networks. NEON's construction phase included offices, labs, towers, aquatic instrumentation, terrestrial sampling plots, permits, development and testing of the instrumentation and associated cyberinfrastructure, and the development of community-supported collection plans. Although colocation of some sites with existing research sites and use of mostly "off the shelf" instrumentation was part of the design, successful completion of the construction phase required the development of new technologies and software for collecting and processing the hundreds of samples and 5.6 billion data records a day produced across NEON. Continued operation of NEON involves reexamining the decisions made in the past and using the input of the scientific community to evolve, upgrade, and improve data collection and resiliency at the field sites. Successes to date include improvements in flexibility and resilience for aquatic infrastructure designs, improved engagement with the scientific community that uses NEON data, and enhanced methods to deal with obsolescence of the instrumentation and infrastructure across the observatory.

Keywords: ecological observatory, infrastructure, lessons learned, NEON, open data

Introduction

The National Ecological Observatory Network (NEON) is a science facility constructed and operated for the National Science Foundation (NSF). Within the NSF, it is funded through the Directorate of Biological Sciences and is operated by Battelle. Battelle is the largest independent nonprofit applied science and technology organization in the world and was awarded the construction and operations responsibilities for NEON starting in 2016. It was recently awarded the continued operations and maintenance of NEON through 2028.

NEON collects and provides free and open data covering the continental scale of the US and the planned decadal scale of the 30-year operational lifespan of the observatory (Keller et al. 2008). NEON was originally envisioned by the scientific community over 20 years ago with the purpose of understanding and forecasting the effects of environmental change (Schimel et al. 2011). The design of NEON is a distributed observatory focusing its data collection and research techniques at the biological systems of our planet (Meier et al. 2023). It stretches across 20 unique ecoclimatic regions in the United States (US) ranging from the Arctic in Alaska to the tropics in Hawaii and Puerto Rico (Fig. 1).

Fig. 1 National Ecological Observatory Network (NEON) is unique, an observatory distributed across the United States including Alaska, Hawaii, and Puerto Rico–with 81 field sites (terrestrial and aquatic), representing 20 broad eco-climatic domains. Each domain represents a different eco-climate. NEON provides a highly coordinated system of open data for monitoring 182 critical ecological and environmental properties (or data products) at multiple spatial and temporal scales. Because of the long-term timescale for NEON operations, the data will be key to addressing fundamental questions pertaining to the drivers and responses to environmental change (figure is a product of the NEON program and can be used by any member of the NEON team. It is open access and may be used).

NEON includes 81 terrestrial and aquatic sites, at which data are collected to enable the production of > 180 data products that are freely and openly distributed to data users around the world through an online data portal (neonscience.org has more details).

The distributed network was designed for the collection of standardized data at multiple spatial and temporal scales. Ecological data collection typically has been and still is usually done on a local scale, with specific research aims by an individual principal investigator. NEON is different from typical NSF funded research in that it is not funded to either directly answer research questions or analyze data and publish scientific results, but instead it is funded to gather the data to help enable researchers across the global scientific community to answer their research questions and supplement their data.

NEON provides highly standardized, free and open data, through its data portal that are interoperable across this incredible spatial scale covering regions across the entire US. Operations for the program are planned for 30 years of continuously collected data.

By design, many NEON sites are co-located with other networks supported by NSF and other US agencies, such as the NSF's Long-Term Ecological Research (LTER) network (Hobbie et al. 2003), the US Department of Agriculture's Long-Term Agroecosystem Research (LTAR) Network (LTAR Network 2022) or the Smithsonian's Forest Global Earth Observatory (ForestGEO) network (ForestGEO 2023).

In addition to operating in concert with other networks in the US, NEON collaborates with similar research infrastructures around the world. For example, the Terrestrial Ecosystem Research Network (TERN) in Australia is another continental scale network covering 15 supersites and producing a range of free and open data comparable to NEON (Karan et al. 2016; TERN Ecosystem Research Infrastructure 2023). While the TERN supersite network began operations in 2009, this network incorporated existing research sites that were already in operation. This model is different from NEON, in the sense that NEON was designed and built as new sites from its inception. In addition to TERN, there are multiple environmental research infrastructures around the world like the Chinese Ecosystem Research Network (CERN) in Asia, the Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research (eLTER) in Europe, and the South African Environmental Observation Network (SAEON) in Africa to name a few.

The aim of this paper is to introduce the mission and design of NEON to a broader international audience. Specific examples from both the construction phase and the operations phase to illustrate what lessons the NEON team has learned from our experience in building and operating the observatory and how this information improves NEON going forward.

Materials and Methods

Lessons learned gathered from personal experience during the construction and operations phases of NEON was used to highlight concepts that would have applicability to other research infrastructures that are being planned, built, or operated. Specific examples from the NEON program along with figures from program status reporting were used to illustrate the lessons learned presented in this paper.

Results and Discussion

Developing and maintaining NEON field sites

Most NEON sites are in locations remote from commercial or residential developments, and none are on land owned by NEON; so during construction the NEON team had to make the sites supportable along with making sure the locations would be usable and supportable for the planned 30-year life of NEON. Designing for supportability included accessibility of the sites not just for NEON field teams to collect data and maintain instrumentation, but also for access to the utilities needed to power and maintain site communications. While direct road and utility access was not possible at every NEON site, it was a critical consideration during the design of NEON sites and the data collection plots associated with each site (Fig. 2).

In the current NEON operations phase, team leadership and field staff work closely with the site landowners, surrounding residents, and the local science community to build strong relationships. This work includes engaging the local community using community meetings and site tours that educate the community on the purpose of NEON, what science NEON is supporting, and the value of the science. The lesson here is that maintaining support from the local community is important for long-term research infrastructures and that open engagement and transparency can help build those strong relationships.

Field Instrumentation

NEON was designed around standardization and the program goals are to always produce comparable data across the US in a standard format. This does not necessitate that instrumentation is always installed the same way at all locations. For example, the aquatic instrumentation, which is mounted in the primary channel of the 24 wadable streams at NEON's aquatic stream sites (Fig. 3), was built during the construction phase using the same design for each aquatic stream site. It was quickly discovered that high flow events in many streams regularly destroyed the infrastructure, thus requiring frequent repair and replacement of infrastructure and instrumentation. To make the infrastructure more robust, the NEON team designed multiple installation configurations that included all the same instrumentation but are built differently to deal with site-specific conditions. These multiple installation designs have all been very successful for their specific locations, significantly reducing damage during high flow events. These have allowed NEON to improve data availability by modifying the original design for certain sites.

Another lesson that the NEON team learned is that site conditions change over time, and weaknesses in instrumentation installations are exposed during these site condition changes. NEON adopted a process of periodically reevaluating the designs and making changes as needed. In addition, NEON has worked with other research projects to incorporate their lessons learned into the NEON program. NEON experienced multiple incidents of floating debris fouling of the navigable river buoy on the Tombigbee River in Alabama that caused damage to instrumentation and dislodging of anchor systems for the buoy. NEON scientists and engineers consulted with the National Great Rivers Research and Education Center (The National Great

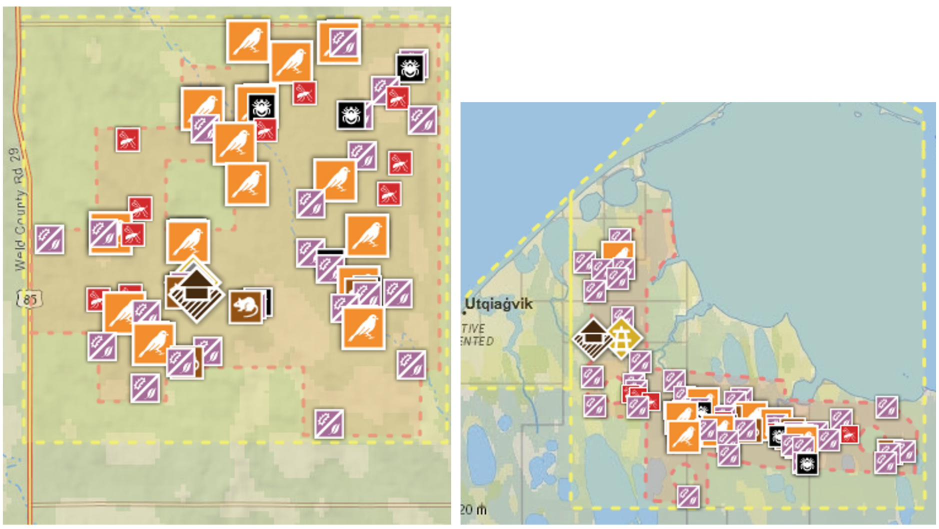

Fig. 2 National Ecological Observatory Network (NEON) site plans for Central Plains Experimental Range (Greely, Colorado) and BARR (Utqiaġvik, Alaska-formerly known as Barrow, Alaska). These sites are representative of design choices that locating site infrastructure near local roads (shown in figure) and in area that have accessible utilities for power and communications. In both cases the surrounding area is rural (farming area in Colorado and Utqiaġvik is a remote village in Alaska only accessible by airplane or ship) (figure is a product of the NEON program and can be used by any member of the NEON team. It is open access and may be used).

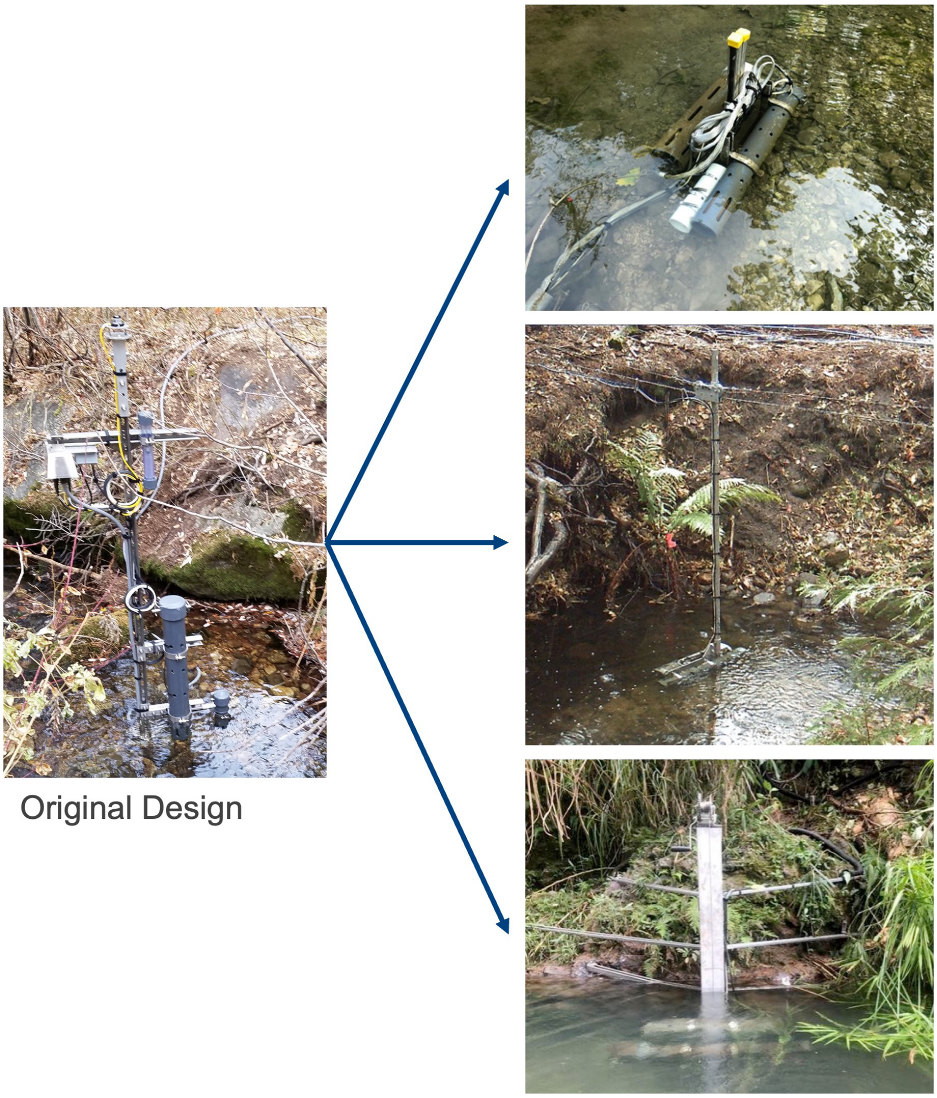

Fig. 3 National Ecological Observatory Network (NEON) aquatic sites have customized mounting infrastructure to deal with individual site conditions and reduce the damage during high-flow events. The original design is shown on the left and three of these designs are shown on the right, including (from top to bottom) lowering the instrumentation supports so that debris can flow over it, mounting instrumentation on overhead cables to allow it to move as the stream flow increases, and attaching to nearby boulders for structural rigidity (figure is a product of the NEON program and can be used by any member of the NEON team. It is open access and may be used).

Rivers Research & Education Center 2013) and the US Geological Survey staff at the Lower Mississippi-Gulf Water Science Center (Lower Mississippi-Gulf Water Science Center 2023) to learn from those programs experience in using buoys on large rivers in the Southeast US. Incorporating the lessons learned from these other programs resulted in implementation of a round buoy at the Tombigbee NEON site that sheds floating debris better and this change has reduced incidents of instrumentation damage and anchoring issues. For a program with a 30-year lifespan, like NEON, very few instrumentation designs will remain the same over the entire program.

The scientific community is NEON's "customer"

The NEON program is about enabling science for researchers worldwide. This means that NEON's customers are the science communities who are looking to access and use the data that is produced on the program. There are three techniques we use to improve the relationship with these communities.

Engagement

NEON has a science engagement team that works with researchers on how to access and use NEON data. The team focuses on early and often engagement activities that encourage a feeling of ownership of the data resources that NEON provides. Also, creating spaces to communicate is very important to our engagement focus. This is done using workshops, participating in conferences, and providing support to individual researchers.

Transparency

NEON continues to improve, based on community feedback, transparency in communication regarding data limitations and issues. This is done by postings data announcements on the NEON website and data portal in addition to adding metadata about data issues and quality within the downloaded data from the data portal.

Inclusiveness

The NEON science team leverages close relationships with the science community to update data collection protocols and make algorithm improvements. This changes a one-way distribution of data protocols and the use of proprietary algorithms to a two-way conversation on improved techniques that includes the science community and learnings from the communities' best practices. To facilities these conversations, NEON has technical working groups that include community representatives to ensure the quality and usability of NEON data.

Operations of a data producing network

Constructing and operating a large and distributed data producing network like NEON results in many lessons on project management that affect the production of high-quality data in addition to the technical lessons described throughout this paper. The operations phase of NEON was originally planned with assumptions that design, engineering, and software development work would be mostly completed in the construction phase and that operations would primarily utilize skills related to data generation, quality control, data publication, and community engagement. This resulted in the skills that were needed to physically construct the observatory not prioritized for retention when NEON transitioned from the construction to operations phase. The first four years of operations, however, have shown that the continuous building of new infrastructure upgrades and repairs is needed to minimize data gaps. This infrastructure is not only hardware, but also software that was developed during construction required continuous maintenance and updating over time also and skills that include engineering and software development needed to be retained into NEON operations.

Another program management lesson relates to budget planning over time. The initial NEON budgets for operations were projected to be flat and they incorporated assumptions on efficiencies that would be found over time to keep costs from increasing. While there have been areas of efficiency found for NEON, the last few years have been a clear lesson for NEON management and the US government that program budgets need to incorporate escalation to cover the maintenance of aging infrastructure and cost inflation over time. Not planning these into the budget will result in less data being produced as repairs take longer and not enough staff can be hired to collect data. These budget planning issues would be increased for countries with smaller science budgets than the US provides to the NEON program. While the NEON budget is sized to cover a scope of over 180 data products across 81 field sites, it still relies on careful analysis of priorities and community inputs and active management of expenditures to reduce cost growth to within available funding levels.

Obsolescence across instrumentation, software, and information systems is also a major issue requiring planning. On a program like NEON, where dozens of instrument types collect data, planning and regular communications with instrumentation equipment manufacturers is key to discovering upcoming issues. Also, when replacing instrumentation with new models, it is very important to build a plan to test the new instruments together with the current ones for data comparability. Similarly on the software side, forward planning of new software releases and upgrades to the underlying data pipeline software is critical. Refreshing information systems for storage and application hosting also needs to be considered in a routine cadence through the life of the program.

Abbreviations

API: Application programming interface
NEON: National Ecological Observatory Network
NSF: National Science Foundation
LTER: Long-Term Ecological Research Network
LTAR: Long-Term Agroecosystem Research Network
ForestGEO: Forest Global Earth Observatory
TERN: Terrestrial Ecosystem Research Network
CERN: Chinese Ecosystem Research Network
eLTER: European Long-Term Ecosystem, critical zone and socio-ecological Research
SAEON: South African Environmental Observation Network

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Author's contributions

CM collected the information contained within and wrote the manuscript.

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Not applicable.

Competing interests
The author declares that he has no competing interests.

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