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Will NEON Kill Ecology?

Efforts by the National Science Foundation to turn ecology into Big Data science may have bombed.

It is a truth universally acknowledged, that a single science in possession of a good fortune, must be in want of Big Data. It so occurred to Scott L. Collins, now Distinguished Professor, Department of Biology, University of New Mexico, who from 1992 to 2003 served as program director, Ecological Studies, at the National Science Foundation (NSF). Collins told *Nature* magazine that the idea for a large ecological observatory sprang from NSF staff who were seeking ways for biologists to get a slice of the agency's Major Research Equipment and Facilities Construction (MREFC) budget. "That put us on a very different footing from the start," he said, "because this was not something that the community and vocal ecologists had wanted."

By the end of 2018, NSF had spent about $633 million to plan, construct, and start operations at the National Ecological Observatory Network (NEON). According to the *Science* magazine reporter Jeffrey Mervis, who has followed the NEON saga closely, the project was proposed in 2000 "not by the ecology community, but by then-NSF Director Rita Colwell. NEON was ecology's entry into the world of Big Data." As articulated in five main funding documents, NEON's goals were grand, vague, and various. In 2004 NEON would "enhance research aspirations, embolden future planning horizons, and transform the scale and scope of ecological research." In 2008 it would "quantify the strong and weak forces regulating the biosphere." In 2011 it would "understand and predict how ecosystems work." In 2016 it would "understand how the biosphere is responding to and affecting earth's physical systems." And by 2017 it was going to "measure the structure, composition, processes, and dynamics of the biosphere."

Not all ecologists were inspired by NEON's Big Data promise, or the Big Biology rhetoric that accompanied it. Gene E. Likens is one of the most respected ecologists in the United States. The cofounder of the Hubbard Brook Experimental Forest, he was elected to the National Academy of Sciences (NAS) and the American Academy of Arts and Sciences and was awarded the 2001 National Medal of Science, the nation's highest science honor, for his contributions to the field of ecology. Together with David F. Lindenmayer, an eminent Australian ecologist, Likens lamented the effect of "the construction of large-scale infrastructure such as NEON" on the "culture of ecology."

Writing in the journal *Frontiers in Ecology and the Environment*, published by the Ecological Society of America, these ecologists argued in 2018 "that passively collecting environmental data … runs the risk of doing science backwards. That is, gathering enormous datasets and then attempting post hoc to determine what to do with those data by somehow producing retrofitted questions."

According to Likens and Lindenmayer, data-driven science is the reverse of the hypothesis- or question-driven science most ecologists pursue. Traditionally, an ecologist might study a species or a local site, such as a lake, a forest, or desert, to answer a question or test a hypothesis related to it and perhaps to others of its kind. According to NSF, NEON would retrain ecologists to become "eco-informaticians" and equip them to join "convergence and translational teams of data scientists, engineers, and domain scientists integrating heterogeneous data sets in new and innovative ways to translate these data resources into increased understanding and human decision making."

Mistrusting what they called a "mindless data-gathering approach," Likens and Lindenmayer worried that "the naïve appeal of technology-driven, remote collection of vast amounts of data, where collection is the end and not the means, threatens to breach the fundamental principles that should characterize good science and evidence-based management and policy."

Big Data ecology, 1970s style

We have seen this movie before. From 1968 to 1974, federal grants of $57 million ($380 million in inflation-adjusted terms) funded the International Biological Program (IBP), which *Science* in 1976 described as an "ambitious effort that was supposed … to revolutionize ecology and usher in a new age of 'Big Biology.'"

In 1965, the National Academy of Sciences impaneled an ad hoc committee on the IBP, comprising primarily mathematically trained systems modelers, which appealed in the following years to NSF for substantial funding. NSF program officers were ambivalent at best about the project, which was touted as an effort to understand "The Biological Basis of Man's Future Welfare." After all, NSF had just been burned by its noncompetitive block grant to the International Geophysical Year, which had recently ended and whose cost had ballooned from $2.2 million to $40 million. David Keck, then program director for systematic biology at NSF, made it clear that the agency would no longer make block grants to end-run the competitive review process required of research proposals.

The NAS ad hoc IBP committee made an end run around NSF and recommended that Congress provide an earmark to NSF funding. A congressional subcommittee, eager to save the planet as Earth Day approached, issued a report stating that IBP addressed "one of the most crucial situations to face this or any civilization—the immediate or near potential of man to damage, perhaps beyond repair, the ecological system of the planet on which all life depends." The report noted that innovative, integrative, cutting-edge, synthesizing computational technology—in 1970 computers with up to 32K memory had become available—would transform our understanding of how ecosystems work. It would be Big Bata, 1970s style. One historian wrote, "Congressmen were as optimistic as the systems ecologists about the potential of computers for solving problems in the management of nature."

Those who advocated the IBP emphasized the need to standardize data in ecology so computers could analyze it. The physical sciences possess clearly defined objects of study—electrons, molecules, field strength, heat—measured in standard units that are articulated and shared as "data." Ecologists, in contrast, have traditionally taken a pluralistic approach to basic concepts; there may be as many ways to define and identify an "ecosystem," "community," or "network" as there are ecologists. According to its planning documents, "The IBP will afford means of standardizing observations and for establishing communication between investigations."

Leading ecologists at the time were skeptical for two reasons. First, although the program might bring extra dollars from Congress, it would present a bureaucratic and logistical nightmare. Ecologists are harder to herd than cats. They tend to be as individualistic as the "systems" they study. Ecologists might not agree about what big-ticket item they wanted. Second, standardization of units and measures may eventually result from progress in ecology, but it would not lead to it. In 1964, foreshadowing the concerns of Likens and Lindenmayer, Francis Fosberg, a botanist skeptical of the IBP approach, wrote: "For ecologists to be required to use specified methods ... would ... be a backward step. In the field of productivity most of the methods that I have heard of are so completely unconvincing that it would seem to be catastrophic to freeze any of them. I would much prefer to encourage originality and hope that some methods that would really measure productivity, or, more correctly, production, might develop."

Starting in 1968, Congress, in response to the NAS committee of systems-theory ecologists, earmarked millions to NSF to fund IBP researchers to use cutting-edge computer technology to model, integrate, and synthesize unprecedented amounts of ecological data in innovative ways. In 1971, the transformative 8-inch floppy diskette drive was introduced. Excellence in computing would promote excellence in ecology. NSF set out to help ecology reinvent itself as a bioinformatic computational science to understand how ecosystems work, to reveal their laws, and thus to inform policy-makers how to manage the processes on which all life depends.

Paul J. Kramer, then a retired Duke University professor and renowned plant physiologist, headed another NAS study on IBP in 1974—this time to evaluate the project. "It started out very badly," he recalled. "There was not enough groundwork done in advance.… It was all thought up at the higher levels by scientific politicians—those scientists who like to develop programs." After NSF made its initial IBP award as a block grant to the IBP committee, which would then distribute funds to universities and scientists, it became clear that the project lacked both scientific leadership and business management. "What management there was," the NAS evaluation observed, "simply evolved as a product of changing situations and the personalities of the scientists involved."

An article in *Science* in 1975 was damning: "Critics suggest that the program has provided funds to second-rate researchers who wouldn't have qualified for grants under the regular NSF grant programs; they suspect that money that might have gone to outstanding individual researchers has been funneled instead to IBP; and they opine that the biome studies have accumulated masses of data while failing to establish chains of cause and effect." Nelson G. Hairston, then director of the Museum of Zoology at the University of Michigan, lambasted NSF for bypassing competitive review in its enthusiasm for innovative eco-biomathematical informatics deploying cutting-edge technologies. He called IBP an example of "ecopolitics," through which NSF officers set up a sexy-sounding program to gin up extra money.

The postmortems written about the IBP agree that NSF made three mistakes. First, NSF brought no organizational coherence to the project. When it was clear the IBP committee could not manage the IBP, NSF switched to making block grants to the individual biome studies the committee had identified—grasslands, tundra, desert, coniferous forest, and deciduous forest. In the subsequent mayhem, empiricists and modelers jockeyed for money and positions. According to a summary in *Science*, "The mode of funding from NSF seems to have precluded effective planning.… There was not enough time to assemble a team to outline and develop a substantive plan for achieving the final goals." Multiyear proposals were hastily prepared and funded in terms of "broad overall goals" such as integration, synthesis, and policy relevance, which "gave little attention to the specific organization of the research."

Second, NSF bypassed the competitive review process it uses for evaluating proposals. NSF typically funds the biological sciences by making modest or moderate grants to individual investigators or small groups at academic institutions where they are accountable to the university's sponsored research office. A principal investigator has overall intellectual responsibility for the project, which, to make it through peer review, will have linked its data-gathering plan to a well-defined question. According to three historians of science, the data-first, questions-later IBP approach "collided with the epistemic goals, practices, and assumptions of many ecologists.… When the program ended, many participants viewed it as a failure."

Third, NSF had not determined a way to curate, manage, and store the gargantuan data exhaust expelled from IBP observatories. The NAS evaluation noted that "storage of the voluminous data obtained was one of the less successful aspects of the IBP." Historians of science have written that data storage occurred as an afterthought in the biome projects. Much of the data that NSF funded IBP to produce might yet be found if anyone wanted it; for example, Wikipedia states that Cambridge University Press published 31 volumes of it. But data produced just because they can be are useless and worthless. Roger Lewin, a British biologist associated with IBP, summarized it as follows: "We underestimated our ability to collect data and overestimated our ability to make use of it."

IBP was a disaster, but it could have been worse. There were two mistakes NSF did not make.

First, it did not commit its Division of Environmental Biology budget to support IBP for the next 30 years. NSF was able to sunset the project in 1976 as a sunk cost and move on. Everyone quickly forgot the IBP experience, including NSF, and the lessons it taught.

Second, NSF could have given priority to proposals from scientists who promised to use IBP-generated data in their research. Instead, NSF allowed ecologists to compete on equal terms for funding even if they did not use IBP-generated data.

NSF waited until NEON to make these mistakes.

Making NEON happen

NSF established its Major Research Equipment and Facility Construction account in 1995. To compete for the MREFC kitty, NSF directorates proposed big-ticket items, such as the Laser Interferometer Gravitational-Wave Observatory (LIGO), large telescopes, and research vessels. This "observatory" money came with a condition. After the observatory was built, the NSF directorate that asked for it would have to use its regular budget to pay the ongoing costs of operations and maintenance.

Rita Colwell, a microbiologist who served as director of NSF for a six-year term between 1998 and 2004 and as president of the American Institute of Biological Sciences (AIBS) in 2008, initiated the idea of a Big Biology observatory. In May 2000, she testified to Congress that NEON would provide a "pole-to-pole network with a state-of-the-art infrastructure of platforms to enable ecological and bio-complexity research." A month after the terrorist attacks of 9/11, Colwell told a meeting of the National Academy of Sciences that NEON could serve as a "biological early-warning system [that] could be used to monitor various locations for disruptions by bioterrorism."

Congress did not immediately provide funding, in part because NEON left unspecified the questions it would answer. But Mary Clutter, then head of NSF's Directorate for Biological Sciences (BIO), defended the infrastructure-first, science-afterward approach. "It's an infrastructure project," Clutter said. "The science will be left up to the merit-review system."

By 2007 NSF awarded more than $13 million to AIBS to "educate the scientific community" about NEON and "to develop the National Ecological Observatory Network (NEON) Coordinating Consortium, NEON Project Office, and preliminary Project Execution Plan." AIBS began by establishing a project, called Infrastructure for Biology at Regional to Continental Scales (IBRCS), to let ecologists in on the idea. The project manager at AIBS, Jeffrey Goldman, compared NEON to "a cruise put together and all of the scientists then go on a ship" built for them. The scientists get on board when it sails; they will then feast on the data buffet it provides. Eric Nagy, a member of the IBRCS steering committee, said, "What I think will happen is we will build it and they will come."

When in 2001 Congress did not bite, NSF officials tried hard to enlist the support of ecologists. Starting in 2003, Elizabeth Blood, who was (and is) a program officer at NSF for

NEON, and James P. Collins, an ecologist at Arizona State University who served as assistant director for biological sciences at NSF from 2005 to 2009, along with other NSF officers, explained to meetings of ecologists how NEON would transform their discipline. But a lobbyist familiar with the MREFC approval process told *Science*, "the ecologists felt that they didn't have to do much because [NSF director] Rita [Colwell] would make it happen."

NSF put MREFC funding for NEON in the 2003 budget it proposed, but once more Congress balked. It was back again in the 2004 budget request. Congress again demurred, as it often does with big-ticket items when they are first proposed. NSF pushed on by making an array of small grants for NEON-related convening, planning, education, and other activities.

After Congress turned down NEON in 2003, NSF commissioned an NAS study. Indeed, major MREFC requests are typically preceded by NAS studies. David Tilman, an eminent ecologist at the University of Minnesota, chaired the NAS appraisal of NEON. In his preface to its 2004 report, he allowed that the committee supported "a NEON-like program" but noted that ecologists "began with little knowledge of or personal participation in the earlier planning process for NEON." The study reviewed NEON *"as envisioned by the National Science Foundation"* (italics in original), which many ecologists considered a fait accompli because leadership at NSF was so committed to it.

Ecologists worried that NEON would skim off funding from the Long-Term Ecological Research (LTER) program, which NSF had established in 1980, in part to continue to support some of the IBP biome studies. (James T. Callahan, who had been the program officer for the IBP, became the LTER program officer.) By 2010, LTER had an annual budget of $30 million and funded research at 26 sites. One ecologist described NEON as "LTER on steroids." But LTER differs from NEON in at least two ways.

First, LTER has supported and provided career paths for ecologists—each LTER study on average included 18 investigators and 20 graduate students. The NEON project does not fund research.

Second, every LTER project is site specific; ecologists gather data in ways appropriate to the site and in response to questions they detail beforehand. Data can be said to be relevant or irrelevant with respect to a given hypothesis and in a given study site; and the hypothesis helps determine what kinds of data or evidence are relevant. It decides which observations are considered as data. NEON, in contrast, takes any possible observation to be equally valuable, as it must be, in the absence of hypotheses. Data take on meaning only in relation to a prior question or hypothesis. Absent a question or a hypothesis, any piece of data is as good as any other.

The goal of transforming ecology into data-driven eco-bioinformatic analysis came down from NSF, not up from the ecological community. NSF's Elizabeth Blood told *Nature*, "We are creating new ways of doing science—ways we can get only a glimpse of now." It was not clear, however, how many ecologists had glimpsed these new ways of doing science or wanted to adopt them. One biologist expressed a common sentiment: "I think if you took the same amount of money and used it to enhance the competitive grants for young people, we'd get [better] science."

Ecology without ecologists

In 2005 NSF established NEON Inc., a nonprofit corporation, to elaborate the design of the observatory and to build it as MREFC funding became available. Ten years later, NSF dissolved NEON Inc. under pressure from the NSF Office of Inspector General, Congress, whistleblowers, and watchdog groups. In all, NSF had awarded about $434 million to the corporation during its 10-year existence.

In April 2007 NSF awarded NEON Inc. about $6 million to refine NEON infrastructure to "include field deployed instrumented towers and sensor arrays, remote sensing capabilities, cutting-edge laboratory instrumentation, … and facilities for data analysis, modeling, visualization, and forecasting, all networked through a cyberinfrastructure backbone." The award also called for the creation of a Science, Technology, and Education Advisory Committee (STEAC) "to be established to provide input and advice from the research community."

NEON Inc. assembled a board of directors, a CEO, a chief scientist, and other officers, and a project team to complete the design the observatory. Notionally, NEON Inc. included member organizations—universities, scientific groups, and other associations—but few representatives showed up for meetings. STEAC was moribund for years.

On October 23, 2006, NEON Inc. issued an "Integrated Science and Education Plan for the National Ecological Observatory Network," which closely followed the Big Data blueprint NSF officers had suggested. This "hierarchically designed national ecological network" divided the United States into 20 ecological domains and placed two "core" observing stations in each. The plan also envisioned 56 "relocatable" stations to be moved occasionally during the 30-year period NEON was expected to operate. NEON differed from LTER because it planned from the start to standardize instrumentation and data protocols across all sites. According to a 2006 planning document, "NEON infrastructure includes a standard set of instruments … in a coordinated framework that delivers standardized, high-quality measurements."

Because NEON is an infrastructure project, as Mary Clutter had said, all decisions that might involve ecologists had been made by 2010 when the design had been finalized and the construction began. The implementation of the plan—the construction of the facility—was and is the work of managers and engineers. The cruise ship could not be redesigned as or after it was built. The message from NSF was clear: "Once we had designed it, [scientists] were somewhat obsolete." The role of ecologists—the only one feasible—was to wait and embark when it sailed.

Michael Keller, a geophysicist, joined NEON Inc. in 2007 as chief scientist, but found that with the completion of the project design in the previous year, there was little for him to do. "NSF's model is that you do the science up front," he said. He referred to the completed NEON design. "And once you come up with the final design, it's up to the project manager to execute it."

When Keller moved on in 2010, David Schimel, a biogeochemist who was the founding CEO of NEON Inc. and the principal investigator on its initial NSF grants, succeeded him. He found it impossible even in his own organization to introduce ecologists into the management mix. "It was difficult to find ecologists with experience in large projects," Schimel told *Science*. "It was equally hard to find engineers and project managers with experience in ecology. And by difficult, I mean impossible—they didn't exist."

"My science role [as chief scientist] was being increasingly marginalized," Schimel said. "I was losing the authority and access to the systems engineering staff and other expertise I needed to do my job." Schimel left NEON Inc. for a position at the Jet Propulsion Laboratory, which (while he was CEO) built a $5 million spectrometer for NEON.

Scott Ollinger, a systems ecologist, succeeded Schimel as chief scientist, but he met the same fate. Ollinger told *Science* that "the number of decisions I tried to make that were overruled reached a point where I felt there was no way I could succeed." Although Ollinger had taken a three-year leave from the University of New Hampshire, he returned in less than a year.

Ollinger thought that NSF excluded ecologists from NEON because it was an infrastructure project and the science, whatever it was, would have to come later through proposals vetted by the customary peer-review process. According to him, NSF program officers, who have authority over every level of a funded project, took the view that "the Observatory can be most efficiently built by project managers with minimal interference from scientists or members of the community." It was and is an infrastructure project; the science would come afterward.

From the time Ollinger left in 2013 to the time NEON Inc. folded two years later, it had no permanent chief scientist. Only one of its principals, Wendy Gram, the chief of education and public engagement, had an ecology background.

By 2010, when NEON Inc. proved unable to hold onto a chief scientist or to make STEAC work, NSF tried to engage with ecologists through a new $20 million grant program to fund proposals from applicants who would use NEON-generated data. NSF has since made it often and abundantly clear that ecologists who "leverage" NEON data will be prioritized for funding. Proposal solicitations from NSF state, "**Proposers are encouraged to use NEON resources, and proposals for substantive and innovative NEON-enabled research will be prioritized for funding**" (bolding in original). In its budget request for FY 2020, NSF said, "The research community is beginning to use NEON data and infrastructure in its research as evidenced by the increase in the number of awards in FY 2018." Pay them and they will come.

May the strong and weak force be with you

Big Science does not require Big Data. The Laser Interferometer Gravitational-Wave Observatory, for example, had a precise mission—the detection of gravitational waves predicted by Einstein's general theory of relativity. Within days after it became operational, LIGO detected gravitational waves produced in the collision of black holes 1.3 billion light years away. The Large Hadron Collider (LHC) sought to detect the long-predicted Higgs boson particle. This was an important step in confirming the theory of the strong force and the weak force in nuclear physics. The strong force holds matter together by keeping quarks within hadron particles, such as the proton and neutron. The weak force or weak nuclear force has to do with the radioactive decay of atoms.

The abstracts of the award documents that fund NEON routinely include this statement: "NEON will provide researchers with a unique capability to quantify the strong and weak forces regulating the biosphere." The idea that strong and weak forces regulate the biosphere and that ecologists can quantify them apparently was thought up as a way to analogize NEON to the LHC. After all, the LHC had received gobs of MREFC money to quantify the strong and weak forces that hold together the nucleus of an atom. Why not use the same language for NEON?

NEON differs from other MREFC projects in two ways. First, projects such as LIGO and LHC asked precise tractable questions that could be stated in hypotheses. Second, they were based on conceptual theories, models, or frameworks in relation to which one could tell what new data meant. In LIGO, for example, a change in the 4 km mirror spacing of less than a ten-thousandth the charge diameter of a proton could be taken as evidence of a gravitational wave emitted from a catastrophic collision a billion light years away. NEON came with neither a tractable question nor a conceptual framework. NEON would produce plenty of data—over 170 "data products"—but it was anyone's guess what these data products might represent or detect.

Ecology is usually associated with the study of the local abundance and distribution of plants and animals. It explores and explains the natural history of sites that ecologists believe reward study and appreciation. Ecologists were not clear about what kinds of "forces" they were supposed to discover at a continental scale. No one has convincingly identified general forces, strong or weak, in ecology or provided empirical evidence of them. But NEON would turn ecology into large-scale Big Data science whether it wants to be transformed or not.

The idea of detecting gravitational waves from a cataclysmic celestial event a billion light years away piqued public excitement. So did the idea of detecting a new particle in nuclear physics. Physicists explained these feats in order to catch society's imagination. NEON in contrast offered no definite discoveries—only boilerplate about transformative science, cutting-edge technologies, innovative computation, excellence, policy relevance, the processes on which all life depends, and other nugatory vacuities. Though not all physicists supported LIGO or LHC, many did. In contrast, NEON seemed unable to bring ecologists together. As the Minnesota ecologist Tilman wrote, ecologists did not participate and were not involved in the planning process. NSF has had continually to sell it to them.

Like actors in a Greek tragedy who cannot hear the wails and prophecies of the chorus, NSF's Directorate for Biological Sciences ignored warnings about NEON Inc. that came from watchdog groups, whistleblowers, the science press, independent auditors, Congress, and NSF's own Office of Inspector General (OIG).

In 2012, when BIO proposed to award a $433.7 million MREFC budget to NEON Inc., OIG commissioned an independent audit that issued three inadequacy memos to the effect that the proposed budget was not auditable and failed to provide the information needed to determine a fair and reasonable price. On September 28, 2012, OIG stated in a memorandum that the audit "disclosed significant questioned and unsupported costs of $154.4 million," nearly 36% of the proposed budget. As a result of its investigation, OIG referred two cases of suspected fraud within NEON Inc. to the US Department of Justice. BIO was made aware of all this but moved forward with the project without waiting for an audited proposed budget.

Starting in 2010 and continuing through 2014, NEON Inc. used taxpayer money to lobby for more taxpayer money—an illegal practice. It contracted with a consulting firm "to 1) develop and implement a targeted appropriations strategy to attract support for NEON; 2) draft letters to relevant members of congress and committees to advocate neon's objectives; 3) coordinate and facilitate meetings between NEON and members of congress and agency officials" and so on. According to the Center for Responsive Politics, it spent $375,000 this way. Tax filings for these four years list these expenditures. NSF personnel did not review NEON Inc.'s income tax returns and either did not know or did not care about them.

Whistleblowers within NEON Inc. reported a frenzy of illegal expenses, "including a $25,000 Christmas party, $11,000 for 'premium coffee services' for NEON employees, $3,000 for board of directors dinners that included alcohol, and $3,000 for T-shirts and other clothing for NEON employees in fiscal 2013," according to *Greenwire*. The science press in articles with titles such as "Ecology's Megaproblem" gave broad coverage to these issues.

In June 2015, NEON Inc. informed BIO that it would be at least 18 months behind in construction and $80 million over budget. James Abrahamson, an independent consultant hired by NSF to review the project, told Science, "NEON Inc. was like a high school team trying to tackle a job that requires the skills of the NBA or the NFL."

Because rules that govern MREFC funding prohibit cost overruns, BIO had to cut back or "rescope" the project to bring it within the budget. NEON Inc. decreased the number of sites from 106 to 81, removed an experimental component of the project, increased the not-to exceed construction budget to $469.3 million, and delayed its scheduled completion date more than two years, to November 2018. BIO transferred about $26 million, which could have funded proposals, from its regular research budget.

James Olds, a microbiologist who then headed NSF's biology directorate, was pleased with the result. He told *Science* in August 2015 that NSF had "identified a descope [sic] option that will keep the project scientifically transformational and should bring it in on time and on budget." James Collins, now chair of the NEON Inc. Board of Directors, concurred that NEON Inc. would still "deliver a ground-breaking research infrastructure for our nation's long term understanding of our ecosystems."

Congress was not good with it. A House oversight subcommittee invited Olds and Collins to testify at a hearing on September 18, 2015, to explain what was going on. (One can watch the entire hearing on YouTube.) In their opening remarks, Olds and Collins defended their stewardship of NEON and reiterated its "potential to transform environmental science." Committee members grilled them about the plague of problems at NEON Inc.; one legislator asked, "Is relieving NEON as the managing entity one of those options that would be considered?" Apparently, Olds had not contemplated removing NEON Inc. from the project. He weaved and dodged, but when pressed, he conceded, "That's certainly an option." Another legislator asked, "Given the total mismanagement by NEON Inc. of this project to date, why should it continue to manage the project?"

All aboard!

On December 11, 2015, Olds dissolved NEON Inc. He wrote to the chair of its board that NSF "has minimal confidence in NEON Inc.'s ability to manage the remaining construction and initial operations of the NEON project." Olds added, "NSF is dedicated to ensuring that further re-scoping will not occur."

Maria Zuber, chair of NSF's oversight body, the National Science Board, said, "If operating costs become an issue, then we may be talking about another descoping."

On April 8, 2016, NSF gave the Battelle Memorial Institute control over NEON as its "sole member." The "cooperative agreement for the transition and completion of the construction and initial operations of NEON" came with three awards worth in total $347,092,473. According to its Office of Inspector General, however, NSF relied on wishful thinking to determine what it would have to pay Battelle. OIG wrote, "NSF awarded funding to Battelle before completing the cost proposal review documents." NSF noted that this arrangement was planned "since costs presented during selection [of new management] could only be provisional given the urgent need to get new management in place." Over the next 18 months alone, Battelle spent $163,822,987 to put Humpty Dumpty together again.

OIG was particularly exercised that the cooperative agreement allowed Battelle to use $1,440,000 of its NSF funding to contribute to various charities it supports. This use of funds "is prohibited in NSF's implementing guidance." OIG found it inexplicable that NSF waived this prohibition while it "acknowledged the charitable contributions were not for the direct benefit of the NSF funded activity."

Yet the explanation is obvious. There was nothing NSF could do about it. Battelle uses a percentage of its funding to support its charities; it made that a condition of the agreement. It is not clear why NSF should have bothered even to review Battelle's cost proposals; it had to pay whatever Battelle asked. NSF had and has no negotiating power. The cooperative agreement was a Faustian bargain, securing NEON at the cost of the research budget.

Battelle brought in two of its senior managers, Richard Leonard and Rick Farnsworth, to run NEON. Leonard, a chemical engineer who had never worked on an NSF project and had no ties to the ecological community, became CEO; Farnsworth, a retired commander in the US Army Reserve who had been with Battelle since 2004, became principal investigator and program manager. Together they are widely credited with completing by the end of 2018 almost all the remaining NEON infrastructure.

Now that the cruise ship had been built and launched, the time had arrived for ecologists to come aboard. Where were they? The Division of Environmental Biology within BIO convened several meetings and workshops to acquaint ecologists with how prioritized they would be if they used NEON data. At one meeting ecologists pointed out that most of the NEON sites were already research sites owned and run by universities, conservation societies, the US Forest Service, and other groups. Protocols governing the gathering, calibration, and identification of NEON data, which "came from high-up," were not useful to the ecologists already doing research where NEON facilities were placed.

These standardized protocols made no sense in the context of their research. "It would be great to design a system where NEON functions within the CONTEXT of the research community, and to work together in a collaborative and cooperative way," one ecologist said. "Many felt the project was moving forward without guidance or buy-in from the community that would eventually use the data," a science reporter wrote.

Conflicts erupted between Battelle site managers and the owners of the already established research sites where NEON observatories were built. Battelle techs are required to adhere to the Big Data protocols that NSF believes promote computational innovation, synthesis, integration, standardization, transformation, and excellence. If data make no sense in situ, so be it. Battelle-NEON does not own any of the land on which the instruments are placed. At one meeting, ecologists suggested that owners of the research sites may stop hosting NEON because it had become more bother than it was worth.

At an NSF BIO advisory council meeting in April 2018, Roland Roberts, director of its biology infrastructure program, noted that NSF needed to "catalyze engagement with the scientific community" and to determine "effective methods to evaluate community engagement and to assess whether NEON is serving the community as intended." NSF could easily assess community engagement if it took its thumb off the scales and let scientists compete for funding on the merits, whether they used Battelle-generated data or not. NEON-related proposals might still come in and some of them survive merit review. Perhaps not. NSF would have its answer.

It is not Battelle's problem whether ecologists use NEON data. Battelle executes efficiently and meticulously the contract it has with NSF to implement the plan designed there between 1998 and 2006. To reach out to the ecological community, however, Battelle created the position of "Observatory Director/Chief Scientist." At first it hired Henry Gholz, who had recently retired as a program manager in NSF's Division of Environmental Biology. Sadly, Gholz died as a result of a fall a few months after he arrived. In February 2018, Battelle appointed Sharon Collinge, a landscape ecologist and professor at the University of Colorado, to the post. "My top priority, as NEON's new Director and Chief Scientist, is to improve and strengthen NEON engagement with the scientific community," she wrote.

She was back at her university job within a year. Collinge ran into the same trouble as had Keller, Schimel, and Ollinger before her. Whatever science planning needed to be done had been done at the highest levels at NSF between 1998 and 2006; after that, NEON had only to be built, operated, and maintained. That is the work of engineers and managers. These are the can-do people at Battelle. Ecologists are epiphenomena.

Rick Farnsworth, who had managed the construction project, left Battelle in December 2018. Three weeks later, Battelle sent executives to its NEON headquarters in Boulder, Colorado, to deliver the bad news that Battelle had fired Richard Leonard, the other principal investigator, and Wendy Gram, who had been the bulwark of ecological science at NEON Inc. "Within minutes they had been escorted out of the building," according to a science journalist. Collinge, who had not been told of these personnel decisions, resigned. Neither Battelle nor the scientists have offered further public explanations for these changes.

When Collinge resigned in January 2019, ecologists sent up a tweet firestorm. Ankur Desai, a prominent ecologist at the University of Wisconsin, tweeted, "@Battelle just fired some of its key science staff (inc Wendy Gram) without input, its chief scientist @CollingeS resigned in disgust [sic], the science advisory committee (STEAC) was dissolved, and @NSF_BIO either can't do much about it or doesn't care." Purdue ecologist Jeff Dukes retweeted Desai with the comment, "And it has a 'Groundhog Day' feel to many." "NEON is once again at a crossroads," Scott Collins said. "How many more crossroads are there before this is just a demolition derby?"

A few months later, in May 2019, NEON came to another crossroads. Members of STEAC jointly prepared and sent letters to Battelle's chief scientist, Michael Kuhlman, who had in January dissolved STEAC and, after the outcry, then had reinstated it. Nine of the 20 members, including the committee's leadership (all current and previous chairs, cochairs, and secretaries), resigned in part because STEAC's governing structure prevented the committee from communicating with NSF and with the scientific community. They said the committee could not operate as an independent advisory group. Ten of the remaining members chose not to resign although they realized "that building an effective working relationship between the remaining STEAC members and Battelle will be challenging." They hoped to "amend STEAC contracts and nondisclosure agreements" to allow STEAC to speak directly to NSF and with the research community.

But Battelle and NSF get along perfectly well without STEAC. It's too late for ecologists to affect NEON or the 170 standardized data products it provides. It may have been a mistake for NSF to have thrown a sop to the research community by creating the committee in the first place. NSF may establish a different committee to try to create excitement about NEON in the intended user community, but it will have no more bargaining power than NSF itself with Battelle.

NSF funded and Battelle constructed the cruise ship; for this there was no need for ecologists. Battelle made an extraordinarily effective effort to salvage the hulk and make it sail. But now, ecologists are expected to get on board. If they do not show up or if, once on board, they try to hop off—whose fault is that?

As NEON goes, so goes ecology

In 2008, NEON Inc. CEO David Schimel told *Science* that the (then) estimated $30 million a year needed for operations and maintenance worried him. "That's the real constraint," he said. "We don't want to gut the community's research budget [at NSF] by building a facility that's too costly to operate." A journalist reported in 2010, "For NSF program managers, the goal was to fund construction of a large-scale biology project without devouring their annual budgets, which nurture thousands of individual investigators."

NEON structures and equipment are expensive, delicate, and exposed. Scott Collins wrote in *The Bulletin of the Ecological Society of America*, "As NEON comes online, we are promised high-resolution data streams from excessively well-calibrated sensors but take all of that with a grain of salt. Sensors can generate lousy data or even periodically fail for a variety of reasons that include environmental causes (e.g., rodents chewing through cabling or UV degradation), or electrical issues." Observation towers attract lightning. Collins included photographs of expensive NEON equipment that had been frazzled in lightning-induced fires and lost to other disasters. The maintenance of 81 complicated observatories also requires keeping good relations with the owners of the sites who might not understand how NEON helps them.

Battelle, which manages the Department of Energy's nuclear weapons laboratories, has shown that it is more than equal to these challenges. It has even embraced NEON as a pet project. Battelle trademarked the NEON logo and included "Managed by Battelle" prominently on it. Any use of the NEON logo requires Battelle's written permission. A typical press release reads, "Battelle 'Eco Force' Will Soon be Fanning Across the Country to Support the National Ecological Observatory Network."

Battelle's new CEO, Lou Von Thaer, talks up ecology. "We have hundreds of people out in field collecting samples," he explained. "They're getting bug bites and sprained ankles and things that we're just not used to seeing as we look at how we operate.... We're making it so that any scientist can get a hold of it and use it for scientific discovery." Battelle uses NEON to present a green corporate image.

Now that the MREFC funding is gone, BIO will have to pay Battelle, no matter how much, to cover operation and maintenance costs, with money that might have gone to ecologists as individual investigators or as collaborators in other infrastructure projects. NEON may not kill ecology, but it will eat its lunch.

NSF's Division of Environmental Biology has taken a step in this direction by announcing that it will not accept any new LTER proposals. LTER projects provided ecologists with academic career paths. Battelle may create a ceremonial post or two for ecologists if they don't make trouble. The many non-temporary opportunities in Battelle's NEON are for accountants, administrators, site managers, field technicians, infrastructure engineers, and data processors. Ecology without ecologists.

How many more times are we going to see this movie? NSF's own Office of Inspector General has tried again and again—and failed—to make NSF-BIO act responsibly. A congressional committee attempted in two hearings to shame NSF-BIO officials, but to no effect. A Greek chorus of science journalists, watchdog groups, consultants, whistleblowers, congressional committees, and many others prophesied in vain. One may expect more outlays or more descoping. The lack of accountability is stunning.

Scott Collins and Alan Knapp, an ecologist at Colorado State University, editorialized in *BioScience* in May 2019, "The Directorate for Biological Sciences at the NSF has committed at least $65 million per year for maintenance and operations of NEON from its research budget, the same budget that funds competitive research grants." The words "at least" are operative. Battelle has as its corporate motto: "It Can Be Done." Whether it can be done for anything like $65 million a year, as NSF imagines, is an entirely different question. Collins and Knapp urged NSF "to consider alternative operations models for NEON—particularly models in which fiscal resources are vested and data collection activities entrusted to the ecological community."

It would have cost around $80 million to terminate NEON in 2016. That's just a bit more than what NSF projects as NEON's operation and maintenance expenses every year. Had BIO understood the economic concept of sunk costs, it might have paid the $80 million once, to free up money to fund ecologists in the future. It is unclear what "divestment" would cost today. For ecologists, however, it might be the only alternative model in which fiscal resources are vested and data collection activities entrusted to the ecological community.

Data, data everywhere—but not a thought to think

The word "data" derives from the Latin for "given." One might suppose, then, that science starts with data. This is true at most only in a psychological sense. Data may arouse a scientist's curiosity and lead him or her to ask a question or propose a hypothesis. To do this, data don't even have to be correct; a dream or a reverie might do as well. As Peter Hempel, who taught philosophy of science at Princeton University, has written, "While the process of invention by which scientific discoveries are made is as a rule psychologically guided and stimulated by antecedent knowledge of specific facts, its results are not logically determined by them; the way in which scientific hypotheses and theories are discovered cannot be mirrored in a set of rules of inductive inference."

Data make no sense. To make sense of data—or to find out which data make sense or would make sense if one could get them—the scientist must be equipped, first, with a conceptual model or intelligible idea of the object or entity he or she wants to study. Second, the scientist must pose a tractable question or hypothesis about that object or entity. Data matter to scientific discovery (other than in the psychological sense just mentioned) only in the context of a conceptual framework, a testable hypothesis, or both. Data produced just because they can be lack meaning and value, even though they flow from "Cutting-edge sensor networks, instrumentation, experimental infrastructure, cyberinfrastructure, support facilities including towers and board walks, and biological sampling plots."

For more than a century, ecologists have struggled, with mixed success, to establish a unifying conceptual framework with which to describe or model the objects or entities they study. They have also struggled to propose general hypotheses that could stand up to counter-evidence without turning into tautologies. With NEON, this struggle is over. NEON science does not bother with the logic of confirmation. It does not bother with concepts or hypotheses. It substitutes for these a set of rules or algorithms of inductive inference—eco-bioinformatics—to translate data directly into understanding with nary a thought or an idea between. Data in, science out. To spin data into knowledge on the loom of bioinformatics, ecologists will join "convergence and translational teams of data scientists, engineers, and domain scientists integrating heterogeneous data sets in new and innovative ways to translate these data resources into increased understanding and human decision making." This will indeed transform ecology. But as Gregor Samsa, the overworked salesman whom Franz Kafka turned into a gigantic insect, learned, not every transformation is a good thing.

Frank Davis, an environmental scientist at the University of California, Santa Barbara, told *Nature* that ecologists do not generally think in Big Data terms. "I think NEON will be ready for ecologists," he said. "But will ecologists be ready for NEON?"

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Recommended reading

Chris Cesare, "Ecology's $434,000,000 test," *Nature* 529, no. 7586 (2016): 274–276.

Scott L. Collins and Alan K. Knapp, "NEON Should Be Run by Ecologists for Ecologists," *BioScience* 69, no. 5 (2019): 319.

Jeffrey Mervis, "Ecology's megaproblem," *Science* (September, 24, 2015).

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Nala Rogers, "The Turbulent Launch of NEON, Ecology's Megaproject," *Inside Science* (January 30, 2019).