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Sedimentary legacy and the disturbing recurrence of the human in long-term ecological research

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Abstract

Even as new elements of a research infrastructure are added, older parts continue to exert persistent and consequential influence. We introduce the concept of sedimentary legacy to describe the relationship between infrastructure and research objects. Contrary to common accounts of legacy infrastructure that underscore lock-in, static, or constraining outcomes, sedimentary legacy emphasizes how researchers adapt infrastructure to support the investigation of new research objects, even while operating under constraining legacies. To illustrate the implications of sedimentary legacy, we track shifting objects of investigation across the history of the Long-Term Ecological Research (LTER) Network, focusing especially on recurrent ecological investigations of 'human disturbance' as researchers shift to study socioecological objects. We examine the relationship between scientific objects and the resources collected and preserved to render such objects tractable to scientific investigations, and show how the resources of a long-term research infrastructure support the assembly of certain objects of investigation, even while foreclosing others.

Keywords

knowledge infrastructures, adaptation, ecological science, Long-Term Ecological Research Network (LTER), scientific objects

In 1941, pedologist Jenny (1941) defined soil formation as a function of climate, organisms, parent material, relief, and time. This formulation gained broad acceptance as an ecological scientific truism, often expressed as the function:

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$$pedogenesis = f(cl, o, pm, r, t)$$

Beginning in the 1970s and mounting thereafter, urban ecologists began to take an interest in how humans and their activities influence soil formation. Left out of Jenny's original function, however, was any explicit role for the human. In response, soil ecologist Richard Pouyat and colleagues (Pouyat, 1991; also Effland and Pouyat, 1997), proposed a new function, now including 'a' for anthropogenic influences:

$$pedogenesis = f(a, cl, o, pm, r, t)$$

More than a theoretical definition for soil formation, such functions shape the practical materials needed for scientific investigations: What data would stand in for '*r*' (relief), what specimens for '*o*' (organisms)? These representative materials are the central focus in this paper, which examines the relationship between scientific objects (such as soil formation) and the resources collected and preserved to render such objects tractable to scientific investigations (such as data or specimens). As scientific objects change, so will the requisite data, specimens, instruments, experts, and so on. In other words, the addition of '*a*' (anthropogenic) as a property of soil formation shifted the scientific object from an ecological to a *socio*ecological one. Furthermore, this shift necessitated changes in scientific practices and the materials employed in these practices: not only a transformation in understanding, but a change in the data and specimens used to understand the object of study.

This shift is especially clear in long-term research infrastructures, which are marked by changes throughout their lifespan, while at the same time relying on and adapting what has already been built, often called 'the installed base' (Star and Ruhleder, 1996). Through our exploration of one such infrastructure that supports investigations in ecology via long-term monitoring and data provisioning, we surface the challenges of aligning sought-after objects of research with the resources made available to render such objects investigate-*able*, or *doable* (Fujimura, 1987). We focus on the role of 'the human' in ecosystem disturbance as our inroad to this struggle, and follow the work of ecologists as they shifted from an ecological object to an increasingly complex socioecological object of research.

Scientific objects are invariably dynamic, shifting with scientific work itself (Mol, 2003; Rheinberger, 2000). Jenny's initial soil function shown above ignored the role of humans altogether – and thus, no data about human activity was needed. Pouyat's later formulation was reparative, seeking to define a role for humans, and consequently suggestive of what data may be needed to conduct such investigations. Yet, even the second function was quickly criticized by soil ecologists as inadequate, sometimes dismissed as an 'add-humans-and-stir' model of soil formation. Indeed, it quickly became apparent that humans and soil formation displayed a more topsy-turvy relationship than a simple additive one. For instance, one of the key organisms in soil formation are worms. During the 1990s, however, ecologists began to recognize that many of the earthworms in North America are invasive species, originally brought over in the dirt used as ballast for ships (Hendrix and Bohlen, 2002). Today, these European and Asian earthworms have significantly transformed how soil is formed in much of North America.

This is an example of how the role of the human in ecological processes can pose a problem for ecologists: How should we think about, categorize, and formulate the role of the human in this case? Are earthworms a manifestation of '*a*', or anthropogenic forces, brought to North America by settlers? Or, are they a case of '*o*', or organisms, with no necessary connection to humans? These dubious distinctions mark long-standing tensions within ecological science about how to approach ecologies and humans, nature and culture. Are colonial earthworms of culture, of nature, or of some other configuration entirely? Even as anthropogenic climate change – or more modest socioecological disturbances such as deforestation or waste-water management – have become pressing scientific and political concerns, ecological scientists have faced a recurrently challenging research object in the human.

Our aim is not to address such *conceptual* challenges in scientific understanding about the division of the social and ecological, but to assess the *practical and infrastructural* response of ecologists to their changing scientific objects. This focus enables us to view the material resources ecologists have amassed to render their novel objects tractable to investigation: How have these scientists sought to align their data collection, instrumentation and collaboration in support of investigating shifting objects of research? We answer this by examining research and data/specimen collection in the Long-Term Ecological Research Network (LTER), a research infrastructure designed to collect, aggregate, and synthesize ecological data over a longer period than the typical time frame for ecological field sites. We explore the history of this research infrastructure to understand how scientists have struggled not only to grapple with ecological concepts, but also to 're-tune' their research infrastructure and foster flexibility in the face of emerging research objects – in particular, socioecological objects.

In other words, we approach our investigation by focusing on the resources that a research infrastructure provides for scientific investigations, such as data and specimens (Ribes, 2014; Ribes and Polk, 2015). In this formulation, research infrastructures enable or inhibit the investigation of objects (such as soil), depending on the resources that are collected, preserved, and rendered available (such as data and specimens). What an infrastructure makes available to researchers can make certain scientific investigations easier or faster, even while making other investigations harder, slower, or outright impossible.

Our central topic, then, is how legacy or the installed base (Star and Ruhleder, 1996) of a research infrastructure has downstream consequences for researchers. Especially, we focus on epistemological and ontological consequences. In a long-term research infrastructure, early decisions in the design of instrumentation and data collection become sedimented, affecting future scientific work. Yet we depart from a simple notion of legacy. We are not telling a story of an unchanging or rigid infrastructure: Across forty years, LTER's members have repeatedly adjusted their data collection to adapt to emerging understandings about anthropogenic forces (such as in soil formation) and socioecological insights. We recount fragments of such changes below. Yet, despite adaptations to the infrastructure, we observe ongoing challenges – downstream ontological and epistemological consequences drawn from how LTER investigators initially formulated their research objects and data collection – which continue to hamper contemporary investigations of the socioecological in ecological science. As such, we argue that long-term research infrastructures display a sedimentary legacy. Sedimentary legacy is a sensitizing concept that draws attention to the resources rendered available by a long-term research infrastructure and the impact that these resources have on the ability to inspect emerging objects of investigation. Consequently, even as new 'strata' of data and specimen collections are added, older strata continue to exert persistent and consequential influences for how a research infrastructure is able to adapt to support novel investigations.

Sedimentary legacy

> We are like sailors who, on the open sea, must reconstruct their ship, but are never able to start afresh from the bottom. Where a beam is taken away, a new one must at once be put there, and for this the rest of the ship is used as support. In this way, by using the old beams and driftwood, the ship can be shaped entirely anew, but only by gradual reconstruction. (Neurath, 1921)

Otto Neurath's well-known metaphor for science – as a ship at sea replaced gradually rather than wholesale – is commonly read as an anti-foundationalist argument (e.g. Quine, 2013 [1960]): Science does not have an unmoved base (such as sense-data or logic) that serves as a firm foundation for science's changing higher functions (such as theory). Our argument for sedimentary legacy bears similarities to Neurath's boat metaphor: We, too, are interested in understanding scientific change without positing some immovable foundation. However, we depart from Neurath in his assertion that, over time, 'the ship can be shaped entirely anew'. Instead, we argue that earlier forms shape the later ones. A fishing trawler at sea will never become an aircraft carrier by the slow replacement of its parts, but a ship made of wood could perhaps slowly become an aluminum one, newly capacitated but of nearly the same shape and size as its forebearer. This is the sensibility we seek to convey in this paper: change that departs from its past yet is still shaped by it.

The concept of sedimentary legacy accounts for both constancy and change and describes the fraught relationship between them. Sedimentary legacy emphasizes the historical accumulation that characterizes long-term infrastructures, which 'sediment' over time, even as new 'layers' or 'strata' of resources are added. In introducing this geological and archeological metaphor, we highlight both change and continuity in the operations of a research infrastructure and particularly how these affect a research infrastructure's ability to make possible, or impinge on, the investigation of novel objects. Contrary to common accounts of legacy infrastructure that emphasize only lock-in, static, or constraining outcomes (Brodie and Stonebraker, 1995; Tilley and Smith, 1996; Weiderman et al., 1997), our approach to sedimentary legacy also emphasizes change to infrastructure that seeks to support new capacities, even while still never fully departing from that constraining legacy. The concept of sedimentary legacy highlights the relationship between long-term infrastructure and the challenge of supporting the investigation of shifting research objects.

In systems theory, legacy refers to 'old systems' that remain in use. Star and Ruhleder (1996) posit that a core feature of infrastructure is that it displays legacy properties: It is 'built on an installed base'. In other words, an infrastructure is built 'on top of' its own past, relying on standards and fitted parts, rather than built *up* or built *out* '*de novo*'. Legacy is a concept drawn from systems engineering (Bisbal et al., 1999; Brodie and

Stonebraker, 1995), adopted and investigated as well by information scientists, librarians, and archivists and software engineers. Brodie and Stonebraker (1995) define legacy information systems as 'any information system that significantly resists modification and evolution'. The 'legacy problem' refers to the variegated challenges of integrating old and new systems, of sustaining and maintaining them or of practically working across them.

Largely, then, legacy has been cast as a problem, such as with Bisbal et al.'s (1999) definition of legacy systems as 'brittle, slow and nonextensible'. More recent investigations from infrastructure studies and studies of maintenance and repair have sought to emphasize the enabling qualities of legacy systems along with the activities of sustaining and renewing them. Jackson (2014), for instance, has argued that maintenance and innovation, commonly cast as opposites, are, in fact, complements. We build on such findings and theoretical assertions by focusing on consequences for the capacity of research infrastructures with respect to the objects of investigation that they support and struggle to support.

Contrary to the narrative in Neurath's boat metaphor, not all 'parts' of research infrastructures can be wholly replaced; many are sedimented, sometimes desirably so. Our concept of sedimentary legacy accounts for the persistent accumulation, or sedimentation, that characterizes long-term infrastructural enterprises. For instance, there can be no substitute for the accumulating archives of data and specimen repositories collected across decades. In Ribes and Polk's (2015) study of a longitudinal cohort study, the Multicenter AIDS Cohort Study (MACS), they emphasize how, by keeping data collection practices 'the same' across decades, these highly comparable and standardized legacy data archives could be repurposed for the investigation of new scientific objects, such as HIV following the treatment revolution. The work of preserving legacy instruments and data archives is closely tied to the capacity of research infrastructure to support the investigation of new scientific objects (Bauer, 2014). Ribes and Polk (2015) use the term 'bounded technoscientific flexibility' to refer to the capacity of a research infrastructure to adapt to emerging scientific objects, and they argue that a key feature of that flexibility is the work of sustaining and renewing the value of legacy resources such as data, specimens, or instruments.

Here we make a similar argument and emphasize that, by repurposing old resources, such as data and specimens, LTER has been able to support the investigation of a new object in 'the human'. Legacy resources can be enabling. However, changes to the key resources have never been able to fully overcome initial decisions for what data to collect and how to collect it: a sedimentary legacy. At its founding, LTER largely eschewed direct data collection about human activities (and thus, human data and specimens in its archives). To this day, LTER researchers still struggle to make claims about humans in ecology, even following reforms to its data and specimen collection enterprises that sought to render tractable scientific questions about human disturbances. Some of the changes to LTER have been significant, such as the expansion of the network in 1997 to include two new urban geographical sites intended to buttress socioecological research. Yet, as we will show, the consequences of the 'older sedimented strata' of data collection have consequences for the 'new layer' and in turn continue to affect how LTER facilitates socioecological research today.

From pristine nature to socioecology: Research infrastructures and their (changing) objects

In 1980, the Long-Term Ecological Research Network (LTER) was founded to support a new approach to ecological science. Rather than the short-term experiments and one-off field studies that characterized much of ecological research, investigators selected six geographic sites for long-term study. Since its inception, LTER has served as a rallying point for a new community of scientists who shared a goal to conduct investigations at the temporal scale of long-term ecological change. The goal was to understand long-term change by 'unveiling the invisible present' (Magnuson, 1990). In turn, the data and specimens that are collected and archived across the LTER sites are made available to the community of ecological researchers to conduct their scientific investigations.

However, no research infrastructure is static, and members are continuously adapting to and preparing for novel scientific insights and emerging techniques. LTER's members have, at various times, sought to shift resource collection efforts to reflect changing research questions. By 2020, LTER had expanded from six to twenty-eight geographic sites, investigating heterogenous ecological biomes, while sibling LTER projects had been founded across the globe. As this paper illustrates, the development of the LTER network has also involved drastic shifts in research objects. Researchers have been increasingly incorporating human impacts and disturbances into their research; they have also sought to understand human interactions with the environment in more complex ways.

Driven by these changing scientific interests, LTER added two new sites in 1997, which, for the first time, focused on 'urban ecologies'. Ecologists Grimm et al. (2000) highlight the reasoning behind these additions:

> Clearly, human actions dramatically alter the functioning of ecosystems of which humans are a part and, equally clearly, humans are a part of virtually all ecosystems and have been so for millennia. Nowhere has this human participation been more intense than in cities, suburbs, and exurbs and in the supporting hinterlands …. The growing impact of urban areas on the face of the earth is reason enough to study them. (p. 572)

In making such changes to their research infrastructure, LTER members have had to manage the tensions between the legacy instruments and long-term monitoring data aimed at ecological objects, and new instruments and monitoring techniques that are required for understanding complex socioecological systems. Socioecological systems theory posits complex dynamics and feedbacks between bio-geo-physical elements and social and economic actors (Berkes and Folke, 1998). This means that socioecological objects are taken to be more than the sum of their parts: They are not studied by simply adding the social to the ecological, as the soil scientists described in the introduction soon discovered. Consequently, socioecological objects demand the adaptation of research infrastructures in order to support their investigation.

The concept of socioecology operates analogously to STS portmanteaus such as technoscience (Latour, 1987) or natureculture (Haraway, 2003): They are assertions of entanglement across concepts once considered discrete. The complex interactions identified by ecologists and social scientists, separately and then in collaboration, have led these researchers to form a new (sub)field of socioecology. In turn, those scientists have argued that LTER, as an infrastructure, should support this kind of research. In part, these efforts have been successful, such as with LTER's 2007 Decadal Plan (LTER, 2007) calling for systematically integrating social science research in LTER, including research on human behavior and values.

But socioecology has had a mixed career within the LTER network. Even while gaining ground – most notably through the creation of the two urban ecological sites in 1997 – social scientists and socioecologists have faced resistance and criticism throughout LTER's history. For instance, in 2011, a 30-year review of LTER deeply questioned the idea of adding social science research to the LTER core research areas, noting that:

> Relatively few leading social scientists have shown an interest in embracing the social science issues being addressed by the LTER network. … With rare exceptions, LTER scientists are untrained in the social sciences and unable to perform social science research of sufficient caliber. Thus, the social science questions posed by the LTER … are too limited at present for such work to be a central focus of the network. Embedded social science as a component of the ecological science questions should continue and expand. However, … we do not think LTER-based social science research will be a central value-added component for the network as a whole. (Michaels and Power, 2011: 12).

In 2019, the LTER network announced that one of its two urban ecological sites, Baltimore, would be sunsetted. The closing of this site presented a major blow to socio-ecological research, closing the door on a home for this emerging form of scientific expertise and its subsequent data and specimen collection.

Part of our goal in this article is to develop the concept of sedimentary legacy, examining both the enabling and constraining dynamics of infrastructural legacy. Another goal is more proximately engaged with the socioecologists of the LTER: We seek to provide an explanation for why socioecological science has struggled to operate within an infrastructure initially designed to investigate disturbances to 'pristine nature'. The concept of sedimentary legacy can help us understand why conducting research on novel objects when relying on an old infrastructure can be systematically and structurally challenging, yet still possible.

Methods

Our investigation is an exercise in historical ontology and epistemology (Daston, 1994; Hacking, 2004) with respect to research infrastructure (Ribes and Polk, 2015). We track shifting and recurrent objects of investigation (e.g. 'pristine nature'/'human disturbance'/'socioecology') across the history of LTER, in tandem with the generation of key resources, such as data and specimens, preserved to support ongoing and future investigations of ecological objects.

Most granularly, our primary investigative strategy in this paper has been to track the concept and operationalization of ecological 'disturbance', one of the five 'Core Research Areas' that was established at the inauguration of LTER. Disturbance is a technical concept in ecology; while it shares many valences with its vernacular meaning, disturbance has received extensive theoretical discussion and debate within ecological science

(Grimm et al., 2017; Pickett and White, 1985; Sousa, 1984; Weaver and Clements, 1938). By tracking the shifting conceptual definitions and discourses around ‘disturbance’ across forty years of LTER history, we follow how concepts are operationalized in ecological work. While we will regularly refer to ‘human and natural disturbance’ or ‘biophysical data’ and ‘human’ or ‘social science data’, these terms and distinctions are not our own. Instead, we have sought to track such distinctions – and later, hybridizations (such as with socioecology) – via the words, practices, and material arrangements of LTER researchers and collaborators.

To conduct this investigation, we turned to the scientific publication record of LTER, along with organizational planning, funding, and policy documentation. We reviewed multiple archives, including LTER site reviews and reports, white papers, and funding proposals. These were accessed from the LTER Document Library (https://lternet.edu/intranet/) and the LTER Zotero Library, and by ‘following’ citations to other research works found in these documents. In total, we coded and analyzed eighty-six documents using a grounded-theoretical approach. In particular, we relied on the ‘methods’ sections within scientific publications to understand how and with what resources ecologists assembled their objects of investigation. We also looked to extensive documentation within LTER about its long-term archival collection and preservation practices. This more narrow investigative strategy was supplemented by many additional primary and secondary investigations of LTER: LTER is one of the most extensively studied research infrastructures within STS and information science, with research having looked at data sharing and interdisciplinary collaboration, practices of data and specimen collection, data and information managers work practice and professionalization, and efforts to develop a common ecological metadata language (Aronova et al., 2010; Baker and Millerand, 2010; Karasti et al., 2010; Zimmerman, 2008). In addition, one author (Ribes) has, at various times over the past 20 years been a collaborator, an embedded ethnographer and a historical analyst of/with LTER. The vignettes below reflect both our broader and more targeted investigative strategy. We delve into particular scientific investigations via publications while also contextualizing these individual studies within the larger tripartite historical trajectory of the LTER research infrastructure.

Instrumenting pristine nature: Vehicle tracks in the Arctic tundra

For this first vignette, we travel to the Arctic tundra to look at how disturbance was addressed in early LTER studies in the late 1970s and early 1980s. Instead of studying direct human impacts, the human was backgrounded as an ‘inadvertent actor’ as ecologists pursued an understanding of a baseline nature without humans. Chapin and Shaver conducted some of these early studies at the Toolik Lake Arctic site. In their paper ‘Changes in soil properties and vegetation following disturbance of Alaskan Arctic Tundra’ (Chapin and Shaver, 1981), they sought to understand why tundra vegetation grows back differently after a disturbance.

When LTER was founded in 1980, the question of anthropogenic climate change was more distant for ecologists than it is today. In what may seem like a contradiction today, LTER’s founders sought to inform the question of human impacts on the environment by excluding them from their investigations altogether, so as to focus on establishing a baseline for 'pristine nature'. As an early LTER planning document stated:

> We know so little about the natural temporal behavior of completely undisturbed ecosystems that a second guideline is to identify a few pristine ecosystems where crucial parameters could be monitored. … The sites selected would be those that were thought to be least likely to suffer catastrophes and to be influenced to the smallest degree by the slow anthropomorphic insults to the environment. Interest in such pristine sites does not imply a disinterest in sites subject to known perturbations. (National Science Foundation [NSF], 1977)

A baseline for nature without humans, or 'baselining nature' (Ureta et al., 2020), could then serve as a contrast to human-impacted environments and quantify those impacts. Through the infrastructure of LTER, researchers would assemble data and specimens to create a benchmark for measuring human disturbance, particularly in light of newly introduced environmental regulations, such as the Clean Water Act, Clean Air Act and the Endangered Species Act. Indeed, this new legislation presented a pressing legal need to not only understand, but also to measure human impacts on the environment, something that even the earliest ecologists wanted to understand (Tansley, 1935).

Returning to Chapin and Shaver's study, in search of a long-term experiment to help them understand vegetation dynamics, they found that, due to oil exploration and pipeline development in the tundra region, 'man has inadvertently established such experiments in the form of vehicle tracks and other disturbances' (Chapin and Shaver, 1981: 605). Their experiment unfolded in sites where, due to human action *as happenstance*, vehicle tracks had marked the tundra and thereafter remained untouched for 7–25 years. Anyone who has walked down an undeveloped road knows that it is common to see tire tracks where vegetation has not grown back the same way as in the undisturbed soil around them. In this Arctic tundra site, however, it was the disturbance itself that offered the opportunity for a 'natural experiment': The tire tracks would signal how vegetation grew back differently in the tracks, an important insight for those tasked with restoring disturbed areas with native plants.

The important thing to note is that, in publication, Chapin and Shaver's experiment was not presented as a study of human impacts. Instead, the human is an incidental, convenient, inadvertent cause of disturbance, leaving behind traces in the form of vehicle tracks that enables one to study more classically tractable ecological phenomena such as plant productivity.

Following this logic, Chapin and Shaver (1981) set up several plots, both in vehicle tracks and control sites, taking temperatures at a soil depth of 10 cm 'on afternoons in mid-August 1976' (p. 607). They collected layers of soil, measured the pH, moisture content and other properties. They gathered plant material from both above and below ground, distinguished live roots from dead, oven-dried them and weighed the biomass. The changes to the environment were reflected in altered shoot size, density and species composition – common attributes of the environment of interest to ecological studies. Meticulous attention was given to establishing field data collection protocols, for example, a standard depth and a certain time were set to measure the temperature and pH of the soil, a consistent amount of wet, oven-dried and sieved soil was measured after rewetting it with distilled water, etc. These detailed protocols for preserving the provenance of plant material were well-established methods in ecological science, and the standardization of these practices and data types was well underway, both within LTER and in the broader scientific community. The human, however, remained merely a faint object of scientific inquiry, a disturbance left behind that allowed for an opportune experiment.

When it was established, the LTER research infrastructure largely mirrored the broader ecological practices in this early period (Kohler, 2002): Ecologists produced data about the environment by taking samples and quantifying substances, measuring temperature and counting species. To measure change through time, data were to be generated by instrumenting, plotting, and counting elements and qualities of the environment longitudinally. In this early LTER Network, however, instruments for understanding the human were absent and no data were collected to address human disturbance as an object of research. While the authors state that 'man's manipulation of the environment' disturbed the soil ecology, their conclusion is directed at 'the importance of below-ground environment in controlling tundra production' (Chapin and Shaver, 1981: 616). Again, the research object in this study was not directed at understanding human impacts, but aimed at using a human disturbance of the environment as an 'inadvertent experiment'.

This is an example of what we call 'the lower stratum' of data and instrumentation, sedimented in the earliest days of this research infrastructure. As we will show, this created a legacy that would influence future research by enabling some objects to be investigated more easily than others.

Coming to terms with sedimentary legacy: Human versus natural disturbance in deforestation

In the previous example of early LTER research, the human was backgrounded to make room for more ecologically tractable objects, such as soil productivity and nitrogen content. However, in the years since, ecological scientists' interests have markedly shifted, as human disturbance has come into view for ecologists as an epistemic object (Grimm et al., 2017). Even as that interest mounted in the form of reconceptualizations about humans in nature, ecologists involved in LTER continued to rely on a long-established set of instruments (and consequently, data and specimens) tuned to quantify chemical and biophysical properties of the environment. For these data and specimen archives to remain useful, they needed to 'repurpose' them using those same resources in order to understand a new object of investigation (Ribes and Polk, 2015).

This change was part of a wider conceptual shift concerning the role of the human in ecological processes. During this period, ecologists were grappling with concepts such as 'ecological equilibrium' (Pickett and White, 1985) and the increasing urgency of understanding impacts such as environmental pollution (Swanson and Franklin, 1988). Despite mounting demands to acknowledge the human as a fundamental component of ecological systems, the struggle to differentiate between 'human' and 'natural' disturbance continued to plague ecologists in LTER. A wide swath of LTER's history can therefore be characterized as a long period of coming to terms with the role of the human in ecological disturbance and its place in ecology more broadly. This struggle has not only played out in the conceptual realm; researchers wrestled with it infrastructurally, as they struggled to adapt data, specimens, instruments, and their geographic sites in LTER to address these changes in the scientific object.

In a study by Steudler et al. (1991), ‘The effects of natural and human disturbances on soil nitrogen dynamics and trace gas fluxes in the Luquillo Experimental Forest LTER site in eastern Puerto Rico’, researchers delineated between different types of disturbance. Specifically, Steudler et al. wanted to understand whether or not there were differences in ecosystem responses to ‘human’ and ‘natural’ disturbance. A closer look at their study highlights an example in which LTER scientists shifted to study the social in parallel to the natural.

For the study, researchers established ‘hurricane’, ‘clearcut’, and ‘reference’ plots. They then analyzed soil properties in the lab and gas exchange in the field. They argued that ‘catastrophic natural disturbances’ were less damaging than human disturbance in the form of clearcutting:

> Although forests may be accustomed to large-scale catastrophic disturbances such as hurricanes, and this may, in fact, enhance forest productivity, forest clearcutting represents a very different disturbance. (Steudler et al., 1991: 361)

The evidence from their study and the division between types of disturbance established a new relationship between human-caused and natural disturbance, creating a distinct category of disturbance: ‘human-caused’.

Although the object of research was changing, the data, specimens, and instrumentation used to understand this new category remained the same as those we discussed in the first vignette for ‘pristine environments’. That is, the same kinds of biophysical data we describe in the previous section now came to stand for human impacts. Data and specimens that were originally collected for the purpose of supporting the investigation of one object of research (natural disturbance of hurricanes), were repurposed (Ribes and Polk, 2015) for the study of different scientific object altogether (human disturbance of clearcutting).

Another example of this dynamic, in which legacy data, specimens, and instruments are used to understand this new category of human disturbance, is a study that explored how streams respond to different kinds of disturbance. In the Coweeta LTER site, Swank (1988) selected twelve watershed sites marked by various degrees of disturbance (e.g. ‘light thinning’, ‘commercial logging’, ‘agricultural cropping’, ‘defoliation by insects’). While the relationship of humans to the disturbance was addressed in the study as a discussion point, the data, specimens, and instruments used to conduct the experiments were, again, biogeophysical resources common to LTER as a whole, such as vegetation types, stream flow, and water chemistry. So, while the human was conceptualized as a potential disturber of ecological systems, human impacts were only captured through biophysical data, such as average annual concentrations of dissolved inorganic constituents for streams draining into treated watersheds (e.g. accumulation of NO3-N, Nitrate inputs and outputs, annual SO4 accumulations). In sum, Swank’s (1988) study operated within the same infrastructure that was designed to measure disturbance at LTER’s inception, which makes the instruments and data collection protocols readily available for quantifying chemical and physical processes of water and soil.

What is absent from both of these studies is any measure of human activities beyond direct changes to the environment – the LTER network was not established to measure ‘the human’, beyond impacts. These are examples of how a legacy infrastructure can become sedimented: The data collected and stored are not ‘human data’, and the archive that was established to understand the original concept of *ecological* disturbance remains. As Pickett and White (1985: 12) pointed out in their influential work on ecological disturbance: ‘Natural change, whether consisting of cyclic replacements or successional trajectories, complicates the testing of hypotheses about human impacts in these systems’. Yet, despite recognizing the difficulty in disentangling the human from natural disturbance, the research infrastructure of LTER remained ‘sedimented’ somewhere between enabling and forcing researchers to repurpose old resources to understand new objects.

Sedimentary legacy as change under constraint: The human as a parcel of green

Our final vignette tracks efforts in LTER to foster new lines of data collection that could account for the *social* in socioecology. Drawing on our stratigraphic metaphor, the biogeophysical legacy data we have discussed above form a ‘lower and older strata’ that was thereafter supplemented by a ‘new stratum’ resulting from specifically human-focused data collection. Here, our concept of sedimentary legacy comes into full view, as LTER investigators added new instruments and data, but encountered challenges with the compatibility of its long-term archive. Ultimately, as we recount, while striving to collect new ‘human data’, the scientists in this study came to favor other data that could be made more easily commensurate with their biophysical data archive, leaving social science-like survey findings to play a peripheral role in favor of large-scale remote sensing data. The consequences are epistemological and ontological – affecting both *how* these scientists know and *what* they come to know – thus demonstrating the long reach effects of sedimented legacy, even in the face of concerted changes to a research infrastructure.

As LTER researchers shifted from exploring unidirectional human *impacts* to the environment to conceptualizing complex feedback loops between humans and the environment, researchers began to incorporate more socioecological systems theory (Grimm et al., 2000) into the field. This new framework was used not just to understand how remote environments, heretofore characterized as ‘pristine’, had been impacted by humans, but also to understand how emergent human and environmental interactions shaped urban ecology. This introduced a new model for urban ecology, buttressed by the addition of two ‘urban LTERs’ in 1997.

Despite this shift in focus, the goal of ‘becoming socioecological’ has been persistently challenging for LTER, even in the urban sites that were intended to support this new research object. For example, as part of the Baltimore LTER site, members conducted a survey of residential lawn care (Law et al., 2004). The survey was administered door-to-door and comprised of two parts: ‘(1) A set of 23 questions and (2) with the permission of the homeowner, soil samples from the lawn were taken to estimate soil bulk density and provide information on general soil chemistry’ (Law et al., 2004). The researchers asked respondents to provide information on the frequency, amount, and brand of fertilizer used per application. This survey thus yielded new ‘human data’, but also a new kind of specimen (i.e. lawn samples closely associated with individual households). A new 'strata' of data, specimens and instruments, continuing in tandem with the development of the old strata, was added as part of LTER's efforts to provide an additional avenue to investigate anthropogenic influences. The published presentation of findings from this survey yielded distinct and granular human objects of research, such as 'attitudes/perceptions of lawn care management' and 'lawn fertilizing practices' (Law et al., 2004). Rather than solely examining physical and chemical processes as with the first two vignettes above, this new survey granted socioecologists the possibility to statistically and theoretically link 'human attitudes' with 'soil', or 'human practices' with 'nitrogen inputs'.

However, in attempting to combine these new data with the long-term archival resources of the LTER, investigators found the new strata to be difficult, even impossible, to commensurate with the old. This is because, while granular, the results of the fertilizer survey data were also small, expensive, labor-intensive to acquire, and provided only a thin temporal slice. Ecologists Zhou et al. (2008: 743) cite the above-mentioned lawn care survey study to state: 'Household surveys of lawn care practices are a valuable tool towards this end, but their effectiveness is limited by their relatively high costs'. No such survey data – for many years and without further significant financial and labor investments in their creation – could be compared to the decades-long data collected in LTER by the more conventional ecological means of chemical and physical analysis. A new approach was needed.

In a follow-on investigation to the lawn care survey, Zhou et al. (2008) sought to find an extensible manner of investigating practices of lawn fertilization, while using an alternative repertoire of data to stand in for the human: remote sensing via aerial photography, LIDAR and satellite data. They noted that household surveys may provide invaluable insights, but do not easily scale to the units of regional ecological analysis, such as watersheds: 'This problem, however, may be solved by modeling household lawn fertilization practices using household characteristics and remote sensing data, which can provide spatially distributed information over large watershed areas' (Zhou et al., 2008: 743). Using aerial and satellite photography and LIDAR instead could serve to oversee vast swaths of residential land. The investigators developed novel analytics that analyzed, for instance, 'lawn greenness' as a stand-in for fertilizer practices: 'Lawn greenness is likely to be affected by households' lawn care practices, such as fertilizer application rates, and thus can reflect the differences in lawn fertilizer application rates' (Zhou et al., 2008: 743).

The small scale of the survey data did not fall out altogether, however, but was repurposed for a new role: to inform and validate (or 'ground truth') the model of lawn greenness. Combining the survey data and the greenness data from remote sensing, the researchers calculated a coefficient that would allow for the evaluation of aerial and satellite greenness data on its own, without the need for validation or inspection of each individual lawn, the painstaking collection of soil samples, or the gathering of specific lawn fertilizing practices and attitudes through survey or interview data.

Our central interest in this article has been the epistemological and ontological consequences of sedimentary legacy. In the case of the lawn fertilizer study, the constraints to their data collection affected the researchers' ability to draw conclusions about human disturbance. Rather than results that speak to human behavior or social dynamics, the findings in Zhou et al.'s (2008) study ultimately illustrate that practices can be predicted by using remote sensing of lawn indices and household characteristics. Yet, while both topics may be of interest to the socioecologist, these are not the same object of investigation. The authors of the remote sensing study are well aware of this as they note: 'In this study, we didn't include one of the very important ecological variables, soil type, because currently, no soils data for the study areas are available at the appropriate scale' (Zhou et al., 2008: 751). To paraphrase: While the small-scale survey could provide a highly granular understanding of soil type, it covered only a very small portion of terrain that these investigators sought to research with the large-scale remote sensing data. Curiously, then, even as the human came into view as an inferred agent of fertilizing, this classic ecological object – soil type – fell out of the model altogether.

As this example highlights, the research infrastructure was adapted to incorporate new instrumentation, data and experts, but ultimately favored sources of data that could be rendered commensurable with older strata of biogeophysical instrumentation, data and expertise. While the infrastructure did change and new objects were made tractable to investigation, it favored those objects most in line with a far older and more sedimented infrastructure. This is because the assembly of resources available allowed the researchers to format the human into a measure of lawn greenness, parcel number, and income level, but notably, not in relation to soil type or particular lawn care practices, which 'did not scale'.

In this final vignette we have examined the development of two new strata of data collection intended to render human disturbance a more tractable ecological object of investigation. The first – a survey of lawn care practices – sought to directly instrument human activity and attitudes. While opening wholly new avenues for the investigation of socioecologies, the survey approach did not scale to the extant units of ecological analysis (such as a watershed), nor to the long-term monitoring goals of the LTER as a whole. Temporally and spatially, the novel, social science-like survey dataset was challenging to commensurate with the long-term, large-scale archives of data and specimens of the LTER. Instead, a second line of data collection based on remote sensing was developed to investigate fertilizer use-levels. This large-scale dataset (not just in terms of the size of the dataset itself, but more importantly its geographic reach) was modeled to stand-in for lawn fertilization via its correlation with greenness, to fit more readily with LTER's extant data. Stratigraphic-metaphorically, two new strata of data were added, but ultimately only one of those new strata could be made commensurate with the older strata of the extant objects of ecological investigation. This demonstrates the ongoing influences of older forms of data collection and associated expertise on the value and utility of new forms of data collection.

Enabling socioecology within an ecological research infrastructure?

In an effort to understand socioecological dynamics in a more systematic way, in 1998, the LTER network laid out its 'Social Science Vision Statement' explicitly calling for the establishment of a 'minimal standard social science capacity' at every LTER site. The shift put 'the human' at the center of the concept of disturbance, complexifying the object itself but also altering the data, experts and the technologies needed to understand this new object. As the authors of the vision statement wrote: ‘Member programs of the LTER Network have long recognized that humans have had significant impacts on their study areas, but these have most often been treated as a form of external disturbance’ (LTER, 1998). Now, it was time to bring the human into the center of the research object itself, this meant assembling data about human activities as well as the experts who took this to be their object: social scientists.

As already mentioned, understanding human influence on the environment has been a fundamental justification for LTER since its beginning, both in its scientific mission and its broader goals of informing decision-making in policy. Efforts to incorporate social scientists are also not new and have been ongoing throughout the development of LTER. Yet, echoing the changed equation for soil formation, where ‘*a*’ for ‘anthropogenic’ was added, throughout LTER’s history, the human has mostly remained a distinct and separate factor, not fully routinized in the data- and specimen-collection activities intended to support future investigations of ecological disturbance.

Socioecological researchers – broadly construed – have sought to shift collection activities to more closely instrument human activity, policy, infrastructure, and institutions, along with expanding the membership of socioecological researchers in LTER. However, rather than anything like the simple ‘add humans and stir’ model of Pouyat’s soil equation, the move to integrate social science into the LTER network introduced several new problems. Some examples of these problems include questions on how to measure and incorporate the human as a scientific object and how to render novel data comparable with the already accumulated archive of ecological resources. Building upon an infrastructure that was initially developed to ‘baseline pristine nature’ has proven more difficult than simply adding or replacing parts. Instead, new goals for the infrastructure have always been weighed against past goals, and more precisely, the weight of incumbent sciences and their accumulated resources (data, specimens, instruments, and expert members) against newer entrants.

Early on, researchers identified the challenges of social research within LTER:

> We expect … institutions, culture, and information – will be the hardest for our biological colleagues to integrate … an equally fundamental parameter, from a human perspective, is determining which state of the ecosystem is ‘socially acceptable’ (Redman et al., 2000).

In other words, how were human intents, values, and normativities to be accounted for? Redman et al. (2000) also noted that a socioecological approach:

> will require new data protocols …. The recognition of the complexity of investigating human ecosystems demands a reformulation of research strategies and methods with the same concern for integration that we call for in our conceptual approach. Once multi-scale techniques are developed, we can begin to emphasize guiding these new methodologies using practical approaches to integration.

The researchers recognized that these new objects – and their attendant new kinds of data and infrastructures – would be necessary in order to understand how socioecological dynamics functioned: They would have to instrument, collect and archive fundamentally different things. Some researchers at another pivotal meeting discussed the need to rethink ‘fundamental research paradigms’ as well as to conduct new and ‘substantial basic research’ (Gragson et al., 2005). By the mid-2000s, uncertainty about how to go about practically incorporating the human as a research object had crept into many LTER discussions and debates. Yet, as a quote from a 2011 report acknowledges, ‘No matter how difficult it may be to achieve high-quality social-science research at LTER sites, we believe that all LTER sites should incorporate appropriate social-science data in their analyses’ (Michaels and Power, 2011: 12).

Conclusion

Fujimura (1987) writes of ‘doable problems’ in scientific research. Rather than identifying the most pressing problems or what recent technical innovations enable, she argues that scientists *articulate* their research questions relative to the resources and techniques they have at hand or can readily assemble. Such a *pragmatic* approach shifts our analytic attention from the intellectual and conceptual elements of science to its situated practice as a matter of what resources and techniques can be brought to bear as a matter of facility, cost, time, and expertise. Similarly, we have focused on how scientists assemble their research objects from the resources their infrastructure renders ready to hand (Ribes and Polk, 2015). The changing objects of research – in this case, human disturbance – presented a challenge to LTER’s conceptual and research frameworks because they could not be easily articulated using the available resources, and they found that the development and value of new resources was necessarily weighed against the old.

Research infrastructures are amenable to additions; we have shown how an old research infrastructure sought to develop new instrumentation and resources for investigating novel objects. However, in a long-term enterprise such as the LTER, legacy resources cannot be discarded or replaced entirely without defying the purpose of long-term research itself: to collect, archive and analyze specimens and data over large time scales and wide geographies. Researchers can, and do, adapt their instruments and data collection routines, but only in ways that are both enabled and constrained by what has come before. This can be seen in how LTER researchers have struggled to incorporate instruments and data that could take human behavior and decision-making into account – something that is arguably necessary to understand when examining human agency in socioecological systems. However, instead of ‘solving’ the issue of incorporating social and ecological data into LTER once and for all, the human has continued to reemerge or recur (Rheinberger, 2000), each time bringing new research challenges. In turn, we can observe a reconfiguration of the research infrastructure which – unlike in Neurath’s metaphor, cannot be ‘shaped entirely anew’ – and instead displays features of sedimentary legacy that are departing from its past, even while shaped by it.

The sensitizing concept of sedimentary legacy draws attention to the consequences of an infrastructure’s installed base. By following how researchers deal with the weight of an infrastructure that was established to study a particular object (pristine nature) as they shifted course to study a new object (socioecology), we have sought to show how a long-term scientific program was constrained by the sedimentary nature of its infrastructure. On the one hand, despite these constraints, this same legacy infrastructure was successfully adapted to support new scientific objects. On the other hand, it always does so within established constraints rather than wholly anew. Sedimentary legacy draws attention to the relationship between scientific objects and their infrastructures, where some objects are made more visible and tractable to investigation than others. We show how these legacy effects or consequences are not merely a matter of social organization, scientific framing or identity, but that they are ontological and epistemological: Both constraining and enabling what scientific objects can be investigated and how they come to be known.

Sedimentary legacy, in the cases we have examined, was not about lacking the will to change, a resistance to social science or some fundamental quality of the human's recalcitrance to research. Certainly, such difficulties are present, and some part of LTER's story may partly be attributed to the challenges of interdisciplinary integration and the recalcitrance of 'the human' to seamless incorporation into legacy ecological concepts. However, our argument and focus has been less cognitive or intellectual and more material: It is the accumulating archives of data and specimens, standardized and routinized instrumentation, and a wide collective of tailored ecological expertise, that present challenges for newer expert groups, with shorter-term archives, far less routinized and expansive instrumentation, and a more nascent scientific expertise. Socioecologists, with their thinner data archives, novel instruments, and techniques, face the uphill struggle collaborating in the same milieu with ecologists that have a long-established wealth of legacy resources. In short, within LTER the cards are stacked against socioecology, though not hopelessly so.

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