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# Elevating the biogeosciences within environmental research networks

*This manuscript is dedicated to our colleague, the late Dr. Henry Gholz, who gave and received much joy in his championing of ecosystem science*

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# Elevating the biogeosciences within environmental research networks

## Abstract

Collaborations between biologists and geologists are key to understanding and projecting how landscapes function and change over time. Such collaborations are stimulated by on-going scientific developments, advances in instrumentation and technology, and the growing recognition that environmental problems necessitate interdisciplinary investigation. Here, we show how the biogeosciences are well placed to answer more completely the core questions that motivate the world's invaluable environmental research networks: specifically, the venerable Long Term Ecological Research networks (LTERs), the newer surveillance facilities of the Earth Observatory Networks (EONs including the USA's NEON), and the geosciences' interdisciplinary network of Critical Zone Observatories (CZOs). Because LTER and EON programs have been supported largely by ecological and biological communities and CZOs largely by the geological community, we assert that a concerted biogeoscience approach across these invaluable networks can benefit both their scientific productivity and usefulness to the wider public.

## 1. A look back to look ahead

Charles Darwin might be utterly unknown today if not for Charles Lyell, whose *Principles of Geology* gave Darwin a realistic and detailed geologic history of the Earth as an ancient, dynamic, life-filled planet. Lyell's three-volume *Principles* were among Darwin's most important books in the *Beagle's* 400-book library (Herbert, 2005). After the *Beagle's* five-year voyage, Darwin's first monograph, *The Structure and Distribution of Coral Reefs*, vigorously embraced geology and biology. Chancellor (2008) described *Coral Reefs* as "not just a book about reefs, it is a book which sweeps across the ecology and geology of the whole world." For his geological and biological contributions, Darwin won scholarly medals in his long lifetime. In his letters, Darwin spoke spiritedly about the concert of geology and biology; "my books came half out of Lyell's brains," he wrote to a colleague (CD Letter to Leonard Horner, 8-29-1844). Darwin's genius was his understanding that biological evolution resulted from the overlap and interaction of biology and geology.

By the early 20th century, growing recognition of the many complexities in biology and geology and a pronounced tendency toward reductionism helped drive biology and geology apart. Many academics welcomed the narrowing of scope and training, and the resulting closer-knit academic communities (Stichweh, 1992). Even today, biology and geology remain largely and formally separated, supported by different university departments, professional societies, funding streams, and journals. Their vast literatures rarely reference the other.

As biology and geology solidified into separate disciplines, a few scholars still bridged the two. Thomas H. Huxley (1897) lectured widely on the overlap of the biological and geological, perhaps best expressed in the essay-lecture "On a piece of chalk". The Russian mineralogist Vladimir Vernadsky (1998), whose *Biosphere* (1926) framed a new science of biogeochemistry, described Earth as hosting photosynthesis, metabolism, chemical cycling, and mineral weathering as globally linked reactions (Figure 1). Vernadsky's vision was shaped by his influential teacher Vasily Dokuchaev, an originator of soil science, one of the most interdisciplinary of sciences.

In the 1930s, Arthur Tansley (1935) defined the ecosystem as an *indivisible* system of biota and environment, and shortly thereafter Lindeman (1942) made measurements and models of the biogeochemical cycles of a lake ecosystems. The young Lindeman (1942) was an enthusiastic proponent of ecosystem science, writing that the "constant organic–inorganic cycle of nutritive substance is so completely integrated that to consider such a unit as a lake primarily as a biotic community appears to force a "biological" emphasis upon a more basic functional organization." Although ecosystem science has always been characterized as interdisciplinary, its scientists have mainly been biologists. Yet, according to Tansley (1935), "Though (as biologists) the organisms may claim our primary interest, when we are trying to think fundamentally we cannot separate them from their special environment, with which they form one physical system". In particular, the renowned G. Evelyn Hutchinson brought a geologist's sense of space and time to ecosystem studies, coring tens of meters into lake sediments to reconstruct the multi-millennial evolution of lakes and their surrounding catchments (Hutchinson and Wollack, 1940).

Like lakes, watersheds lent themselves to the new systems analysis. By the 1930s, hydrologic responses of watersheds were being quantified (Hursh et al., 1942) to better understand land-use effects on the hydrology of soils, hillslopes, and catchments (Figure 2). These findings inspired ecological scientists, and the concept of "watershed ecosystem" was actively used by Bormann and Likens in 1967 to quantify ecosystem-wide "nutrient budgets, erosion, and weathering … if the ecosystem is a watershed … and … is underlain by a tight bedrock." Questions about bedrock leakiness of watershed ecosystems spurred collaborative drilling and groundwater studies between ecological and geological scientists (LaBaugh et al., 2013), certainly foreshadowing future collaborations among ecosystem and critical zone scientists.

In the early 1980s, the US-NSF (National Science Foundation) established the Long Term Ecological Research (LTER) network, which accelerated progress in ecosystem science. The LTERs joined forest watershed studies with other long-running studies that now include grassland, desert, boreal, Arctic and Antarctic, coastal, marine, tropical, mountain, farming, and urban environments. In the early 1990s, the U.S. LTER network facilitated the development of collaborations called ILTER, which today is an international network with 44 members and over 800 research sites (Mirtl et al., 2018). In the late 20th century, Magnuson (1990) wrote that the LTER objective was to uncover "hidden" ecological processes that only play out over decades and centuries or longer and LTER ecologists Swanson and Franklin (1988) reached out to geoscientists in a paper in *EOS* (the news outlet of the American Geophysical Union), as they foresaw that the expansion of ecological time scales in LTERs could tighten relations with Earth scientists, who often had comparable interests although with generally longer timescales of study (Figure 3).

In addition to the LTER and ILTER networks, environmental science is today being advanced by two new and distinctly different research networks. First, are the biologically oriented Earth observatory networks (EONs, of which the USA's NEON may be the best known). The EONs are facilities that take a surveillance approach to the environment, generating, storing, and sharing big environmental data across large spatial scales, aimed mainly to detect changes in ecological conditions and biodiversity (Walters and Scholes, 2016, Lindenmeyer et al., 2018). Second are the new geo- and Earth-science supported program of

Critical Zone Observatories (CZOs), question-driven research observatories that now operate in more than 25 nations, designed to study an expanded ecosystem from the atmosphere and vegetation to the deepest groundwater and weathering rock (Jordan et al., 2001; Brantley et al., 2006; Richter and Billings, 2015; Giardino and Houser, 2015).

Two of the world's major environmental networks, the LTERs and EONs, have been supported largely by ecological and biological science communities (Schimel and Keller, 2015; Groffman et al., 2016; Lindenmayer et al., 2018), whereas the CZOs are supported largely by the geological community (Brantley et al. 2006). Given that the three networks are conceived as the environmental analogs to astronomers' super-telescopes, ocean scientists' research vessels, and geophysicists' seismic networks (Chabbi and Loescher, 2017), it seems reasonable to ask whether there should be a more concerted effort to integrate a biogeoscience approach within these invaluable environmental networks. Many scientists expect such an initiative can benefit biological and geological research and education (Hedin et al., 2002; Billings et al., 2012; Larsen et al., 2015; Field et al., 2016; Hinckley et al., 2016; Johnson and Martin, 2016; O'Neill and Richter, 2016; Willig and Walker, 2016; Brantley et al., 2017b; Grant and Dietrich, 2017), and are motivated by the opportunities that the biogeosciences create for young ecological and Earth scientists (Wymore et al., 2017).

The objective of this paper is to motivate more collaborators to bring the best of the biogeosciences to the LTERs, EONs, and CZOs. We wish to rally researchers who trace their intellectual heritage back to Hutchinson, Lindeman, Tansley, Vernadsky, Huxley, Gilbert, and Dutton, and of course Lyell and Darwin, to work across these networks to help solve pressing environmental problems and puzzles. We propose a biogeoscience-focused initiative as one way to maximize scientific and educational returns from these large network investments.

## 2. The three environmental networks

Despite disciplinary boundaries, the biological and geological sciences have exerted positive influences on the development of LTERs, NEON, and CZOs. LTERs integrate geological properties, processes, and legacies in their studies of watersheds, biogeochemical cycling, and land-use change. EONs focus on biologically and ecologically relevant measurements arrayed across strongly varying environmental gradients, and have embraced monitoring of the atmosphere and the belowground environment as part of their efforts (Schimel and Keller, 2015). CZOs include biological studies of vegetation, animals, and microbes to assess the role of biota in driving critical zone processes (Brantley et al., 2007; Chen et al., 2016; Winchell et al., 2016; Brantley et al., 2017a). In fact, the core concepts that motivate these networks' operation clearly and substantially overlap (Figure 4), that is, ecology's ecosystem is entirely congruent with Earth science's critical zone (Richter and Billings, 2015).

Still the three networks differ in important ways. EONs are surveillance facilities that make large datasets available for scientific use, whereas LTERs and CZOs perform this service as a byproduct of their efforts. The LTERs and CZOs are place-based centers for research with science communities working on question- and hypothesis-driven science. We expand on these distinctions below, and note that while networks in the USA may be emphasized, discussions with international colleagues are most important about paths forward in the integration of the biogeosciences within and across environmental networks in all countries.

### 2.1 LTERs

LTER networks are well into their fourth decade and operate on all continents. Their overall program goal is to quantify ecological processes that operate at temporal scales longer than can be addressed in individual research projects of few years' duration. The networks are composed of diverse sites, intentionally including the remarkable diversity of many of Earth's ecosystems. The mission of the USA's LTER, which in broad outline is comparable to many ILTERs, is to "provide the scientific community, policy makers, and society with the knowledge and predictive understanding necessary to conserve, protect, and manage … ecosystems, their biodiversity, and the services they provide" (27 December 2017; *https://lternet.edu/node/20*). There are many specific reasons why the LTERs have proliferated so widely, not the least of which was demonstrated by the policy importance of long-term field studies of the environmental effects of acidic air pollution in the 1970s, 1980s, and 1990s (Likens and Bormann, 1974; Abrahamsen et al., 1994; Johnson and Lindberg, 1994).

LTER research emphasizes question-driven ecology and environmental biology. Five research themes guide the USA's LTER research and include plant primary production, organismal population studies, movement and cycling of organic and inorganic matter, and patterns of and response to disturbance. Urban LTERs have research themes that emphasize land use and land use change and human-environment interactions. Studies across the LTER network examine ecosystem structure and function as it responds to changes in temperature and precipitation, sea level rise, invasive species and changes in management and disturbance regimes. While the sites range from the Arctic to the Antarctic, from forests to prairies to deserts to cities, and from coastal to oceanic, there is a common goal of understanding and being able to predict the structure, function and services of these diverse ecosystems.

Research at LTERs employs experiments, comparative studies, as well as long-term monitoring. Timescales of interest mainly range from the instantaneous to the multi-decadal. Some of the greatest achievements of the LTERs come from their support of hundreds of long-term field experiments, many of which are conducted at the watershed scale. The inter-generational transfer of long-running experiments from older to younger scientists is a high priority in the LTER (Knapp et al., 2012; Willig and Walker, 2016).

## 2.2 EONs (and NEON)

Most EONs to date are facilities and surveillance projects that accumulate and manage monitoring data that are important to the ecology and biology of a site and region (Figure 4). EONs are not question-based or hypothesis-testing projects (Lindemeyer et al., 2018) but are rather networks of observational facilities that deploy highly controlled measurement and data collecting systems. The resulting large data sets are intended to facilitate broad, hypothesis-driven research of ecological change over time and space.

The USA's NEON has a 30-year vision and has many dozens of site locations systematically selected to span the wide ecological gradients of the USA. The network aims to integrate site-based information collected from high frequency sensors, physical samples, and regional observations including high-resolution remote sensing. Once fully operational, NEON will be the first continental scale EON facility that systematically monitors a large common suite of ecological processes both above and belowground (Kuhlman et al., 2016).

NEON's mission is to analyze and forecast impacts of climate, land use, and invasive species on ecological processes at the regional to continental scales. NEON intends to enhance spatial scaling of ecological processes across broad ecological domains, quantify temporal trajectories of ecological processes, and estimate uncertainties of environmental forecasting (Schimel and Keller, 2015). NEON will provide interested researchers and resource managers access to tightly controlled, high quality, ecologically relevant data. With the current vision of

NEON (and EONs in general), the majority of data characterize ecological and biological components of ecosystems, on relatively short time-scales (instantaneous to decadal), including atmospheric dynamics, and in relatively surficial layers (i.e., up to 2-m depth) of the belowground ecosystem. The current NEON operations design has minimal capacity to respond to emerging issues as well as new priorities that result from our evolving understanding of complex ecological systems and unexpected system behavior. Increasing such capacity, rather than relying upon a 30-year fixed data stream on sentinel organisms and processes, is critical if NEON is to remain transformational throughout its 30-yr lifespan.

Recently, NEON renewed a call for greater engagement with the scientific community, requesting advice "on the programmatic direction of NEON in order to … provide the highest scientific rigor … as well as inform and provide input on designs, data product algorithms, (and) best community practices…" (Kuhlman et al., 2016). As a network of facilities, NEON and all EONs are all dependent on scientist involvement. We respond to this request by arguing that NEON can ensure much greater scientific engagement by incorporating more geophysical and biogeophysical aspects of the biogeosciences into their overall design and operations.

### 2.3 CZOs

The concept of Earth's critical zone was first described by Ashley (1998) and Jordan et al. (2001), and within a decade, the USA's NSF had launched a program of CZOs that today includes nine landscape- and watershed-based field observatories in diverse climates and regions. Critical zone science is not a repackaging of an older science, but a new science that encompasses the processes and structures across the full depth and volume of the aboveground atmosphere to

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the weathering fronts deep within Earth's weathering profiles (Anderson and Anderson, 2010; Anderson et al., 2013; Brantley et al., 2006; Brantley et al., 2011; Chorover et al., 2011; Richter and Billings, 2015; Grant and Dietrich, 2017). While the mission of critical zone science is to discover how Earth's living skin is structured, evolves, and provides critical functions that sustain life, due to the extreme diversity among critical zones, each CZO, just like the LTERs, tests hypotheses relevant to a place-based assessment of the local system.

All USA CZOs also actively support a core of common measurements, emphasize the need to develop models that cross temporal and spatial scales, and participate in cross-CZO studies pertinent to critical zone structure and function. Across the USA's CZO network, studies focus on questions about biotic-abiotic interactions driving landscape and critical zone evolution, responses to extreme events such as floods and drought, wildfire, and accelerated erosion, interconnections of surficial and deep critical zone structures and dynamics, and responses of critical zones affected by a variety of human activities (Hahm et al., 2014; Rempe and Dietrich, 2014; Oshun et al., 2015; Rasmussen et al., 2015; Billings et al., in press). Studies across this network examine CZ functioning as it responds to phenomena such as major flooding in the Front Range of the Rocky Mountains; wildfires in Idaho, California, and Arizona; millennia of rice cultivation in southeastern China; hurricanes in Puerto Rico; historically devastaing agricultural erosion in the USA's Piedmont; tile drainage and intensive agricultural management in the USA's mid-west; urban and agricultural forcings on river basins across France, monsoonal climates in the Western Ghats Mountains of India, and a century of irrigation with Mexico City's untreated wastewater in the agricultural fields of the >100,000 ha Mezquital Valley. Studies also focus on critical zone architectures developed under the influence of Quaternary climates (Anderson et al., 2012; Anderson et al., 2013) and associated biota, in response to tectonic forcing (Tucker and van der Beek, 2013; Brocard et al., 2016; Willenbring et al, 2013), and internal system dynamics (Attal et al., 2015).

The critical zone, like the ecosystem, spans spatial scales from vegetation-clad soils and weathering profiles, to hillslopes and catenas, small watersheds, river basins, entire continents, and even the globe (Richter and Billings, 2015). The critical zone concept embraces timescales from those of the meteorologist to those of the deep-time geologist. This relatively young interdisciplinary science has educated and enthused many students, a number of whom are now advanced post-docs and active young professors (Wymore et al., 2017).

## 3. The biogeosciences can enhance environmental networks

The three kinds of environmental networks can work much more closely, as the ecological and Earth sciences have many shared interests. That the concepts of critical zone science and ecosystem science are closely related indicates that biologists and geologists can collaborate and leverage investments made in instrumentation, infrastructure (e.g., informational and physical), and expertise across the LTERs, EONs, and CZOs. We call on scientists to accelerate their production of ideas, papers, and proposals for biogeoscience research and education, and to support such research at place-based research sites and across environmental networks.

Supported by workshop grants, research coordination grants, or simply by conference calls, scientists and students need to inventory research-questions, metadata, and measurement protocols of all network sites. The information will reveal the coverage of data and the data gaps in the three networks, providing scientists with the opportunity to perform meta-analyses, develop and test hypotheses cross-networks, and propose projects to fill data gaps.

## 3.1 The biogeosciences and EON/NEON

How the biogeosciences can enrich environmental research networks might be most readily seen with EONs and, in particular, NEON in the USA. To ensure comparability of data across spatial scales and over time, NEON has adopted highly standardized sampling protocols for all measurements, including those associated with the Terrestrial and Aquatic observing systems. As NEON is a network of facilities operated by a centralized national office, expanding the scope to include the biogeosciences would involve additional implementation of ancillary instrumentation and data collection.

Engagement activities (i.e., workshops) involving the biogeoscience community can be organized around: 1) data quality and utilization, and 2) additions of critical zone instrumentation. First, biogeoscientists can help determine how NEON will address: integrating model observations across large networks; integrating biophysical, theoretical and conceptual models; and identifying knowledge and programmatic gaps to advance our ecological literacy. Secondly, engagement activities also need to address how to most efficiently expand the purview of NEON from what is traditionally viewed as ecological (i.e. vegetation and soil surface horizons) to the full critical zone. Because most of NEON's current observations are made to a maximum depth of 2 m, a design modification strategy is specifically needed to expand NEON's scope via deeper collections, drilling, and the installation of sensors and samplers across the full biogeochemical weathering profile down into water table aquifers and unweathered substrata. Hydrologic measurements can be enhanced, geomorphological investigations conducted, and landform evolution evaluated via many tools including cosmogenic isotopes. We suggest this could be accomplished at NEON's 20 core terrestrial sites via joint proposals from biological and geological scientists to guide deep-sensor installation, deep sampling, coring, and bringing the latest in geophysical, geochemical, and geobiological approaches to NEON's 20 core sites. The extension of NEON as an ecological-critical zone network might in part be funded by NSF's Geosciences instrumentation programs.

Engaging the biogeosciences community in this manner will have additional reciprocal benefits for NSF, NEON, and the ecological research community. Such engagement will strengthen support for and commitment to NEON among researchers today and for the next generation by providing scientists with opportunities for greater involvement in this powerful research platform. NEON, in turn, will achieve higher quality science as a result of renewed intellectual input from scientists, increased flexibility in its operations, and continued strength in its networked instrumentation platform.

### 3.2 The biogeosciences and LTERs and CZOs

Ways in which we can promote enhancement of the biogeosciences in the research question-driven LTERs and CZOs can be found in the LTER and CZO literature itself. For example, in the special 1990 issue of *BioScience* dedicated to the then decade-old LTER program, LTER scientist John Magnuson (1990) described how groundwater flow paths, through many tens of meters of chemically and physically contrasting glacial tills, controlled lake water chemistry and thereby much of the biological functioning of lake ecosystems (Figure 5). In biogeochemical studies of the North Temperate Lakes LTER in Wisconsin, Magnuson showed how alkalinity varied among lakes by over an order of magnitude, and was entirely determined by the catchments' glacial history. Such detail was not only important science, it expanded the lower boundary of the ecosystem and increased understanding of how landscapes neutralize acid pollutants deposited from the atmosphere (i.e., in acid rain).

Other examples of research derived from explicitly biogeoscience approaches are illustrated in the scientific history of the co-located Luquillo LTER and CZO in the humid tropical forests of Puerto Rico. At Luquillo, the biogeosciences are in full bloom with LTER and CZO scientists together conducting studies of biogeochemical redox reactions (Hall and Silver, 2015, Hall et al., 2016), biotic-lithologic controls of surface water chemistry (McDowell et al., 2013), and forest, stream, and landscape processes that span instantaneous to multi-millennial timescales (e.g. Shanley et al., 2011; Brocard et al., 2015; Dialynas et al., 2018). Luquillo's research on lithologic knickpoints that control the evolution of up-catchment soil formation, plant productivity, and whole landscape dynamics, may become a classic in the biogeosciences (Brocard et al., 2015).

In spite of the benefits of the biogeosciences approach, relatively few LTER sites have comprehensively characterized structures and processes of subsoils, regoliths, and weathering rock and sedimentary substrata. Coring and drilling campaigns through soil and weathering profiles present great opportunities to learn more about how ecosystems function as watersheds and landscapes (LaBaugh et al., 2013; St. Clair et al., 2015; Riebe et al., 2016), about how terrestrial and aquatic ecosystems are tightly linked, and about how ecological processes function over Earth's history. Cosmogenic and isotopic analyses can provide unprecedented chronologies of landscape residence times and new understandings of geologic erosion and the biogeochemical cycling of nutrients and trace elements (Bierman and Nichols, 2004). Contemporary geophysics and geohydrologic approaches can characterize structures and functions of subsurface architectures (St. Clair et al., 2015), trace the movement of water across and through hillslopes (Fan, 2015; Evaristo et al. 2015), and help these environmental research sites meet core objectives. Urban LTER projects in Baltimore and Phoenix in the USA have been centers for the integration of ecological, biophysical, and social sciences

(Groffman et al., 2016). Bringing a cadre of Earth scientists into urban LTERs will help develop important new understanding of cities' surface and subsurface structures and processes.

The biogeosciences can enrich the Earth sciences' CZOs by helping to integrate more biological process research to balance a strong Earth science focus. While most CZOs characterize vegetation and microbial composition and functions, relatively few CZOs characterize microbial genetic responses to environmental cues that drive key biogeochemical reactions, or the dynamics of plant-microbe- or plant-animal-critical zone interactions such as the mycorrhizal studies of Chen et al. (2016) or the gopher studies of Winchell et al. (2016). Recent work highlights vegetation-critical zone interaction (Brantley et al., 2017a), effects of pests, pathogens, bioturbators, wildfires, plant-animal interactions, and land management are far from fully explored (Bastola et al., 2018). More systematic measurements of CZO plant, animal, and microbial responses to changing land use and climatic conditions could go a long way to enhancing understanding of ecosystem and critical zone functioning.

For LTER and CZO networks, we suggest research agencies consider crafting open-ended RFPs in the biogeosciences that encourage creativity and excellence from teams of ecologists and Earth scientists. Both site-based and cross-site research proposals can be solicited to advance the biogeosciences within NSF's environmental networks. Proposals for research should also be open to post-doctoral fellows and young scientists, with provision for small projects and travel grants to develop wide participation from biology and geology communities.

## 4. Conclusions

Despite the radical interdisciplinarity of many of the founders of the biological and geological sciences, for over a century these two disciplines have developed with relatively little interaction. More often in parallel than together, biologists and geologists have studied the Earth's diverse ecosystems and landscapes; the circulation of water, energy, and chemical elements; and the dynamics of the planet's living and non-living systems.  Given that the world's environmental research networks such as the LTERs, EONs, and CZOs have grown largely from either biological or geological science communities, we argue that a more explicit biogeoscience approach in these networks would increase our understanding of how feedbacks among biologic, hydrologic, physical, and chemical processes condition landscape functions and structures. Such a biogeoscience initiative could help better address a variety of pressing human needs as well.

There are growing numbers of biologists and geologists working together on societally important issues. Top-tier, multidisciplinary journals now publish biogeoscience papers and professional ecological and geological societies have new biogeoscience journals and subdivisions. The venerable and highly cited journal *Biogeochemistry* has been in publication since 1984. New biogeoscience awards and lectureships are funded. Cambridge University Press just published a major volume, *A Biogeoscience Approach to Ecosystems* (Johnson and Martin, 2016). While there remain much heavy lifting and many details, there are many good reasons to bring an explicitly biogeosciences initiative to the world's LTERs, EONs, and CZOs. Such an effort can greatly increase these network's individual and collective values for research, education, and society at large.

## Author contributions

Dan Richter prepared the manuscript with contributions from all co-authors. All co-authors researchers at LTER, EON, and CZO sites and many participated in the 2015 LTER All-Scientists Meeting in Estes Park, Colorado (proposed by Tim White) and in 2017 discussions of a Work Group on CZO-LTER Collaboration.

## Author conflicts

The authors declare that they have no conflicts of interest.

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## Figure captions

Figure 1. False-color composite of global photoautotroph abundance, integrated from September 1997 to August 2016. Vladimir Vernadsky gave special attention to solar radiation driving global photosynthesis and subsequently the biological, geological, and human responses that follow from this remarkable transfer of "cosmic energy". Largely unknown in the English-speaking world in his lifetime, some consider Vernadsky to be the equal of Darwin in the significance of his understanding of the biosphere. The image displays ocean chlorophyll *a* concentrations from dark blue at ~0.05 mg/m$^3$ to green at ~1 mg/m$^3$ to red at >30 mg/m$^3$, and land normalized difference vegetation index from a minimum as brown to a maximum as dark green to blue. (Image is provided by the SeaWiFS Project, NASA/Goddard Space Flight Center).

Figure 2. By the early 20th century, precipitation and streamflow was being measured in watersheds, for example at Coweeta Hydrologic Laboratory in western North Carolina where a) a deforestation experiment in Watershed 17 quantified catchment hydrologic response and divided surface from subsurface discharges (Hursh et al. 1942). Today, watershed-ecosystem studies continue to quantify hydrologic responses to land uses but with greatly advanced instrumentation as is shown in b) the Stringer Creek Watershed in Montana (Hood et al. 2006), in which within watershed processes such as water storage, interflow, groundwater recharge, gas exchanges, nutrient flows, evapotranspiration, and other processes are estimated with sensor technologies, often in real time and supported by LiDAR-generated digital elevation models.

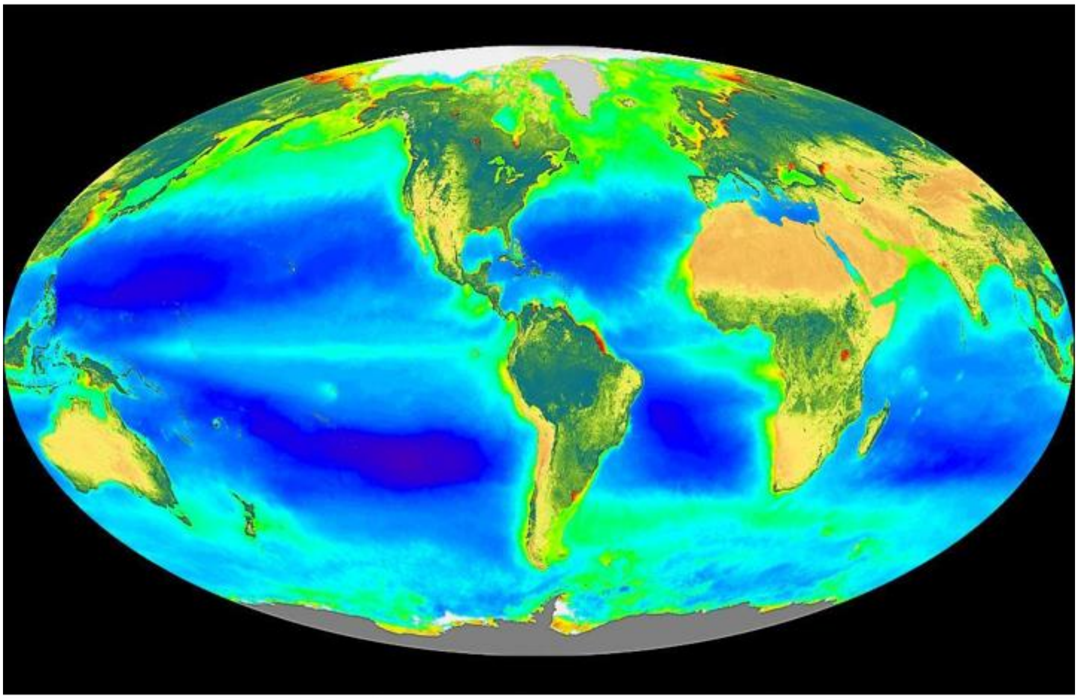
Figure 3. A semi-quantitative space-time diagram of the sort used to justify LTER's emphasis on extending ecosystem research into longer timescales and wider spatial scales (modified from Wu 1999). Spatial-temporal scales of interest in ecology and Earth sciences overlap from narrow to wide, and from instantaneous to multi-million years.

Figure 4. Conceptual models of a) ecologists' ecosystem (Lindenmayer and Likens 2009, after Bormann and Likens 1967), b) Earth scientists' critical zone (courtesy of Southern Sierras Critical Zone Observatory), and c) ecologist's surveillance

design at one of NEON's core terrestrial sites (courtesy of USA's National Ecological Observatory Network).

Figure 5. An example of geohydrological, geochemical, and geohistorical control over lake water chemistry, biology, and ecology. The diagram (slightly redrawn here) was used by Magnuson (1990) as justification for expanding space and time scales for ecological research. The figure illustrates the relatively slowly operating hydrogeologic processes of groundwater flow through contrasting glacial tills. Dilute water from Crystal Lake (~10 µmol/L $HCO_3^-$) arrives at Big Muskellunge Lake with greatly elevated alkalinity (~350 µmol/L $HCO_3^-$) due to flow paths of groundwater that extend tens of meters deep through carbonate-rich substrata. The example illustrates the overlapping of biological and geological sciences with regard to space and time.

Figure 1.



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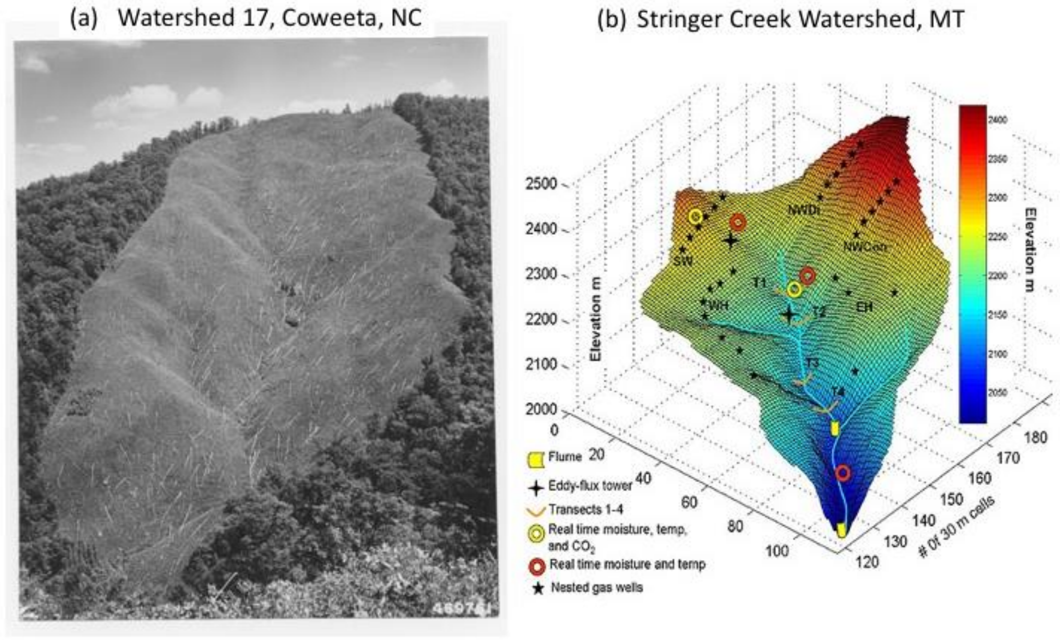

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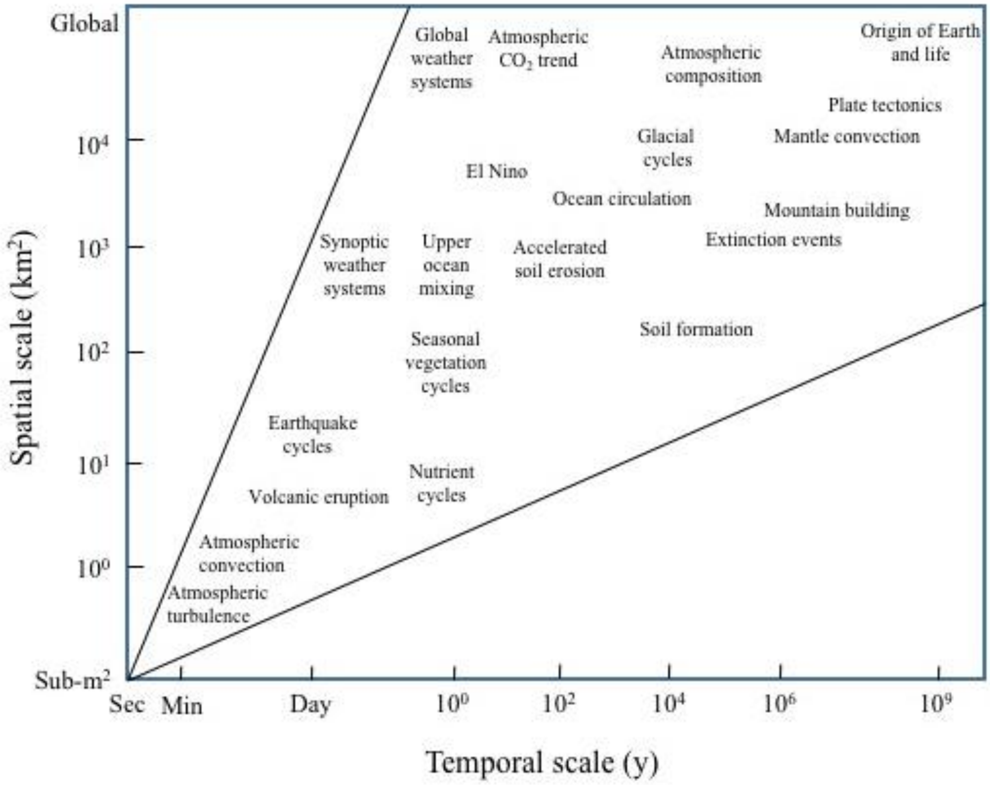

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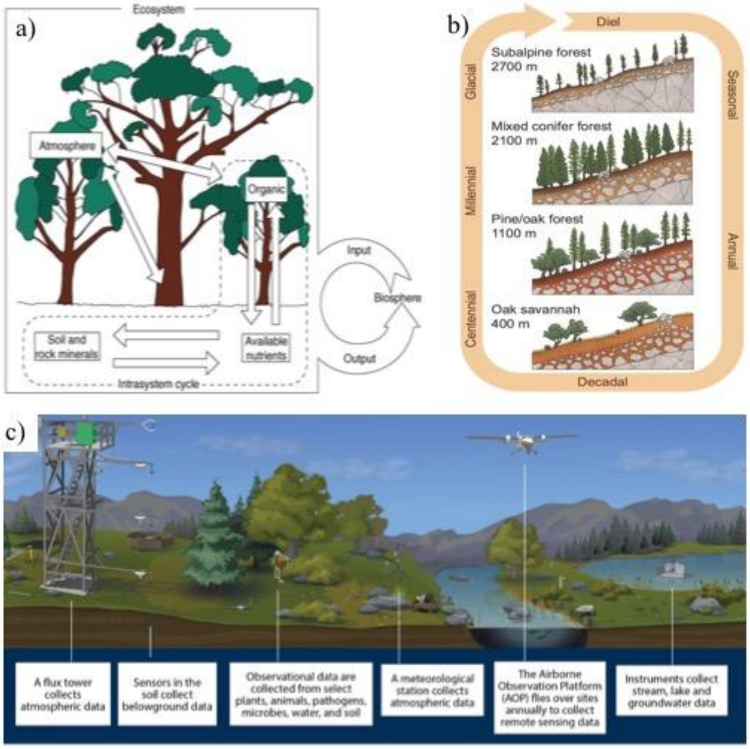

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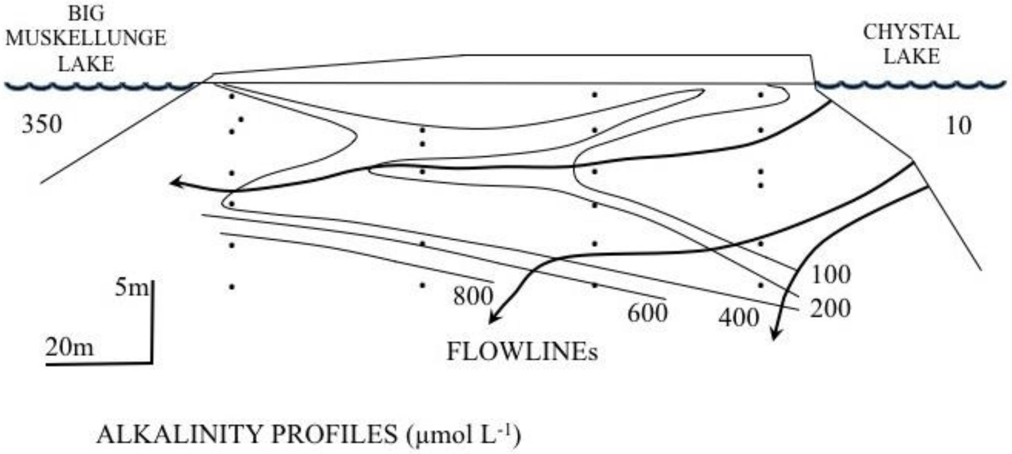

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