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Synergies Among Environmental Science Research and Monitoring Networks: A Research Agenda

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Key Points:

- Cross-network syntheses linking research and monitoring networks in ecology (e.g., Long-Term Ecological Research and National Ecological Observatory Network) are beginning to provide results
- To date, syntheses focus on co-located sites in both networks, rather than multiple ecosystem processes at regional to continental scales
- Future syntheses in six broad research areas could realize the power of these networks and open them to the broader scientific community

Supporting Information:

- Supporting Information S1

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Synergies Among Environmental Science Research and Monitoring Networks: A Research Agenda

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Abstract Many research and monitoring networks in recent decades have provided publicly available data documenting environmental and ecological change, but little is known about the status of efforts to synthesize this information across networks. We convened a working group to assess ongoing and potential cross-network synthesis research and outline opportunities and challenges for the future, focusing on the US-based research network (the US Long-Term Ecological Research network, LTER) and monitoring network (the National Ecological Observatory Network, NEON). LTER-NEON cross-network research synergies arise from the potentials for LTER measurements, experiments, models, and observational studies to provide context and mechanisms for interpreting NEON data, and for NEON measurements to provide standardization and broad scale coverage that complement LTER studies. Initial cross-network syntheses at co-located sites in the LTER and NEON networks are addressing six broad topics: how long-term vegetation change influences C fluxes; how detailed remotely sensed data reveal vegetation structure and function; aquatic-terrestrial connections of nutrient cycling; ecosystem response to soil biogeochemistry and microbial processes; population and species responses to environmental change; and disturbance, stability and resilience. This initial study offers exciting potentials for expanded cross-network syntheses involving multiple long-term ecosystem processes at regional or continental scales. These potential syntheses could provide a pathway for the broader scientific community, beyond LTER and NEON, to engage in cross-network science. These examples also apply to many other research and monitoring networks in the US and globally, and can guide scientists and research administrators in promoting broad-scale research that supports resource management and environmental policy.

Plain Language Summary Today many research networks and monitoring networks exist in ecology and environmental science. Their complementary designs and publicly available results and data can create powerful synergies. Long-term, hypothesis-based mechanistic research can provide context and

explanations for data produced by monitoring networks while the standardization and broad coverage of monitoring networks can provide context for Long-Term Ecological Research (LTER). Recent efforts have combined results and data from two US-based science networks: the LTER network and the National Ecological Observatory Network (NEON). We describe how these initial efforts could be expanded in six broad areas, that would provide opportunities for the broader scientific community to engage with LTER and NEON, and may also be relevant to other cross-network syntheses in the US and globally.

1. Introduction

Ongoing changes in the Earth system and its component ecosystems affect environmental quality and human health and well-being (Weathers et al., 2016). To predict and mitigate such changes, research in environmental sciences must address continuing challenges in understanding Earth's biogeochemical cycles; the causes and consequences of biological diversity and climate variability; changes in freshwater resources; controls of infectious diseases; and land-use dynamics (National Research Council, 2001). Research and monitoring networks collect environmental data and make it publicly available (Hampton et al., 2013). Efforts to synthesize across networks can support progress toward these grand challenges.

Many studies have outlined the potential for the scientific community to address challenges in environmental science using concepts and data from multiple environmental science networks (e.g., Hinckley et al., 2016a). However, progress toward this goal is limited by lack of understanding of ecological insights that can be gained through syntheses of existing data, including testing of outstanding hypotheses and the generation of new hypotheses (LaDeau et al., 2017). Specifically, there is a lack of understanding of how the complementary structures of various networks might be used to formulate research syntheses. In addition, research agendas or frameworks are lacking that connect research questions to available data for specific combinations of existing networks in ecology and environmental science.

This study aims to fill these gaps. We explore the potential for combining long-term experimental results and hypotheses from research networks with highly standardized long-term observations from monitoring networks to elucidate the mechanisms that drive long-term ecological and environmental change. Our objectives are to:

1. Describe types of environmental science networks and their complementary features
2. Assess the progress to date for cross-network synthesis studies of Long-Term Ecological Research (LTER) and National Ecological Observatory Network (NEON), and
3. Identify opportunities and challenges that build on the work accomplished to date

We highlight potential synergies between the LTER Program, a research network, and the NEON, a monitoring network, both funded by the US National Science Foundation (NSF) (Collins & Childers, 2014). Both networks address major challenges in environmental science and make their data publicly available for use by researchers, educators, policy-makers, and others. Our findings are also relevant to other research and monitoring networks in the United States and internationally (Richter et al., 2018). These networks include the Critical Zone Observatories (CZO) (White et al., 2015) funded by NSF; the Forest Service Experimental Forests and Ranges (e.g., Lugo et al., 2006) and agricultural experimental watersheds and ranges (Bartuska et al., 2012) funded by the U.S. Department of Agriculture; the AmeriFlux network funded by the Department of Energy (Novick et al., 2018); the international Global Lakes Ecological Observatory (GLEON) (Hanson et al., 2016); programs managed by the United States Geological Survey (USGS, 2016); and the cooperative National Atmospheric Deposition Program (NADP) (see supporting information).

In this study, we describe the results of an NCEAS working group on LTER-NEON synergies. The working group included scientists from LTER, NEON, and the broader ecological community whose research draws on environmental research networks. In two workshops and successive discussions, we analyzed the structure of LTER and NEON and their complementarities (Section 2), created a typology of synthesis efforts (Section 3), and evaluated the progress to date and challenges and opportunities for future efforts in six broad research areas of ecosystem and environmental science (Section 4).

Table 1
Basic Attributes of Two Types of Networks for Environmental Biology: Research and Monitoring

Attribute	Research	Monitoring
Why	To test mechanistic hypotheses explaining ecological processes.	To monitor ecological processes and environmental conditions.
Who	A community of researchers designs and conducts the research and make data available.	Science and technical staff design sampling strategies, collect data, conduct lab analyses, manage data and make data available.
What	Observational studies and manipulative experiments test fundamental concepts.	Data are collected and processed based on standardized protocols, sensors, and technologies
How many	Funded individually in response to solicitations.	Selected as part of an overall sampling design.
Where	Locations proposed by groups of researchers. See Table S1, Figures 2 and 3.	Selected by an overall sampling design. See Table S1, Figures 2 and 3.
How often	Must seek renewed funding on a case-by-case basis.	Funded for a predefined period.
How long	May adopt and continue datasets from prior efforts.	Predefined duration.

Note. Research networks are focused on answering research questions and are bottom-up, whereas monitoring networks are focused on data collection and are top down. Examples of research networks include NSF's Long-term Ecological Research sites, as well as other examples in the text. Examples of monitoring networks include the National Ecological Observatory Network, as well as others mentioned in the text. Some networks in environmental biology may have attributes of both research and monitoring.

2. Principal Features of Research and Monitoring Networks

While many networks encompass both aspects, research and monitoring networks have distinct designs and administration (Table 1, Table S1, Figure S1). Research networks (e.g., LTER, CZO, GLEON, US Forest Service Experimental Forests and Ranges [USFS EFR]) focus on question-driven research, based on observational studies and experiments that test mechanistic hypotheses about ecological processes, and are designed and conducted by a community of researchers, who make their data available. Sites may be funded individually, and may seek renewed funding on a competitive basis, based on agency guidelines and priorities. Sites in research networks may adopt and extend prior long-term studies, and engage in synthesis efforts across sites, but synthesis among sites may be limited by inconsistent methods. In contrast, monitoring networks (e.g., NEON, NADP, USGS National Water Information System [NWIS]) focus on long-term, standardized data collection of patterns in a set of predetermined variables, based on a predefined sampling design. Science and technical staff manage instruments, lab analyses, and data collection, quality control, and archiving procedures. Data collection involves standardized protocols, sensors, and technologies and data are collected using a predefined sampling frequency. Sites were selected and are funded as a group, for a specified period. While the dichotomy of network types illustrated in Table 1 represents well the differences between LTER and NEON, many other networks share features of both research and monitoring networks as defined here.

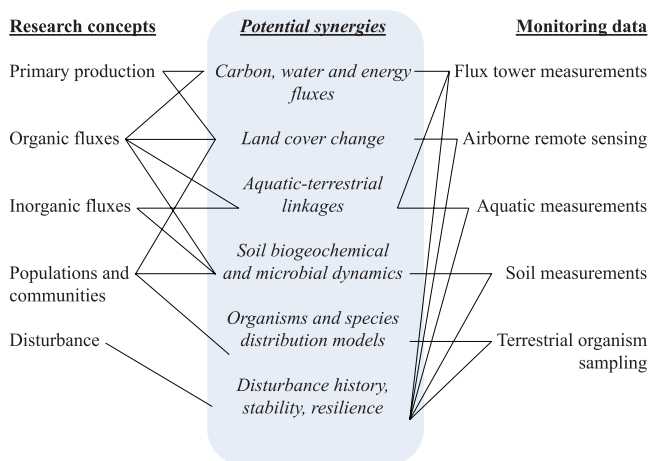


Figure 1. Synergies between research networks and monitoring networks are powerful because they link research concepts to monitoring data. In this example, core areas of inquiry in a research network (Long-Term Ecological Research [LTER]) and major areas of standardized measurements in a monitoring network (National Ecological Observatory Network [NEON]) provide complementary contributions to potential synergies that address key questions in environmental science.

We identify synergies between research and monitoring networks, using the US LTER Program as an example research network and the US NEON as an example monitoring network (Figure 1). Synergies between LTER and NEON arise from their complementary designs: LTER focuses on mechanistic understanding of ecological processes, and provides conceptual models, hypothesis-testing, long-term experiments, temporal coverage, and information management, while NEON focuses on quantification of ecological trends, and provides consistent design, standardized measurements, spatial coverage, and a data resource (Figure S1).

The LTER Program, a research network, was initiated in 1980 and presently includes 28 sites in a wide range of ecosystems (Callahan, 1984, <https://lternet.edu/site/>, Figure 2, Table S1, Table S2). Researchers propose sites, establish the research agenda at each site, and conduct research on long-term ecological processes. The five core areas: primary

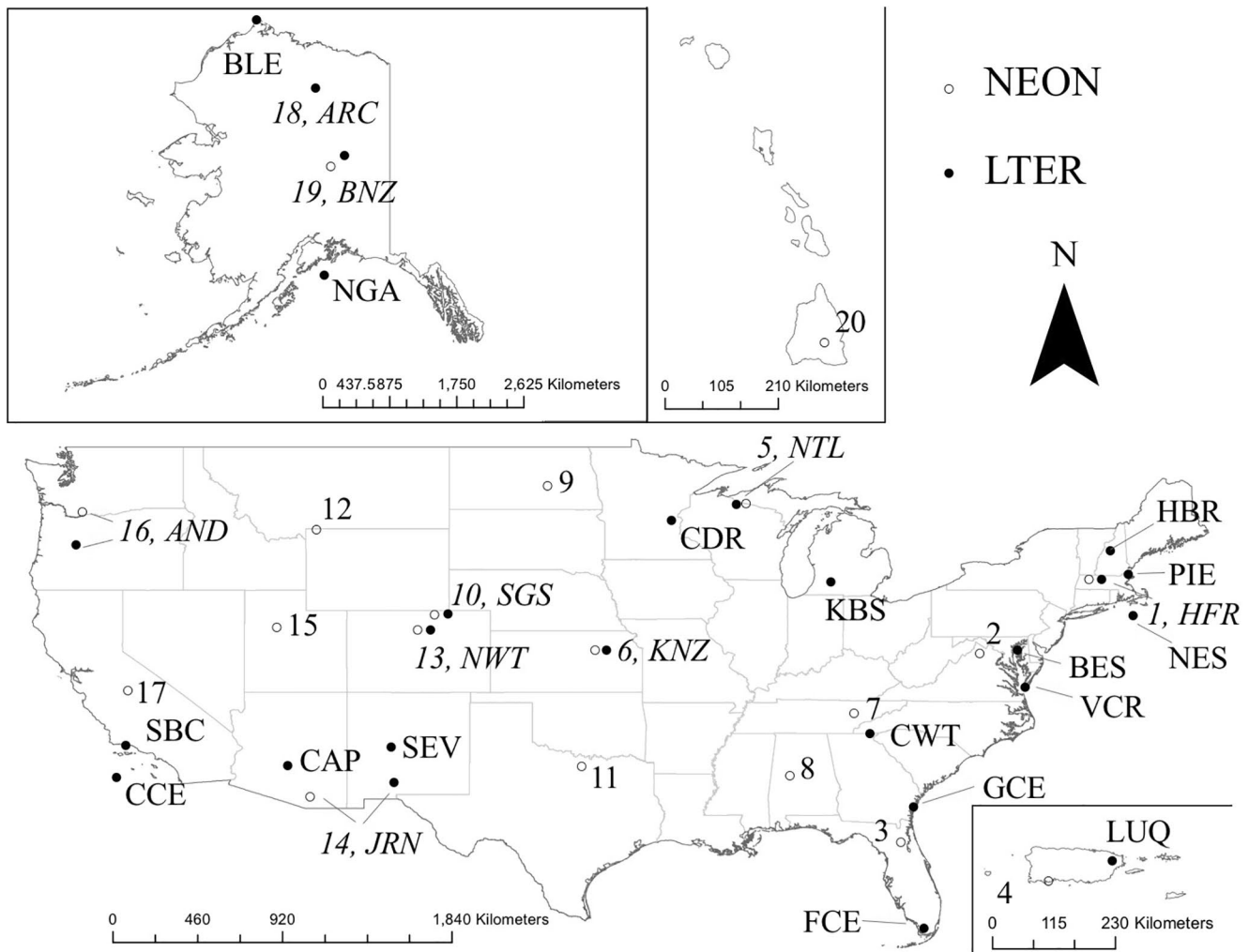


Figure 2. Physical locations of sites in the NEON and LTER networks. NEON core sites are shown as open symbols; LTER sites are shown as closed symbols. Numbers refer to NEON eco-climatic domains, and three-letter acronyms refer to LTER sites (see Table S1). Further details on site locations are available at <https://lternet.edu/site/> (LTER) and <https://www.neonscience.org/about-neon-field-sites> (NEON).

production, population studies, movement of organic matter, movement of inorganic matter, and disturbance (<https://lternet.edu/core-research-areas/>) provide a research framework for synergies that address major questions in environmental science (Figure 1). Data are available from the Environmental Data Initiative (<https://environmentaldatainitiative.org/>).

NEON is a monitoring network, which began to provide data in 2015, and was designed to examine ecological change over time at a set of 47 terrestrial and 34 aquatic sites selected to represent the diversity of eco-climatic domains in the continental U.S. (Kampe et al., 2010; Kao et al., 2012; Goodman et al., 2015; Springer et al., 2016; Thorpe et al., 2016; <https://www.neonscience.org>, Figure 2, Table S1, Table S2). The network includes 30-year installations in core “wildland” ecosystems within each of the 20 NEON domains as well as additional sites that cover environmental variability within the domain. The major measurements of NEON include flux tower measurements, airborne remote sensing, aquatic measurements, soil measurements, and terrestrial organism sampling to document how U.S. ecosystems are changing (Figure 1, supporting information). NEON data are available via the NEON data portal (<https://www.neonscience.org/data/about-data/getting-started-neon-data>).

NEON was designed by the research community, including LTER researchers. Its top-down standardized measurement programs complement the bottom-up, research-question driven approaches in LTER. Prox-

Table 2
Six Approaches to Synthesis That can Build Synergies Across Research and Monitoring Networks to Address Fundamental Questions in Ecology and Environmental Science

Type	Goal	Approach	Research network contribution	Monitoring network contribution	Requirements
1) Single process or property, across sites	Generalize patterns and processes among locations	Test concepts about a single property or process across locations	Concepts and hypotheses about ecological mechanisms across locations	Data on ecological properties across locations	Comparable measurement methods
2) Multiple properties or processes, within site	Elucidate relationships among processes at a location	Test concepts about interactions among properties or processes at a single location	Concepts and hypotheses about mechanisms linking ecological processes at one location	Data on multiple complementary properties at a location	Measurements of complementary processes or properties at a location
3) Multiple properties or processes across sites	Generalize patterns and elucidate relationships among processes and locations	Test concepts about interactions among properties or processes at multiple locations	Concepts and hypotheses about mechanisms linking ecological processes at multiple locations	Data on multiple complementary properties at multiple locations	Complementary and comparable data at all locations
4) Across temporal scales	Generalize patterns and processes across temporal scales	Test concepts about a single property or process across temporal scales	Concepts and hypotheses about ecological mechanisms across temporal scales	Data on ecological properties at multiple temporal scales	Comparable measurement methods
5) Across approaches	Generalize effects of methods on data	Test effects of methods on a single property or process	Concepts and hypotheses of causes and effects of methods	Data on a property collected using different methods	Different measurement methods of same property or process
6) Modeling	Refine models and identify data gaps	Test concepts about properties or processes	Concepts and hypotheses about ecological mechanisms	Data on ecological properties	Measurements relevant to model variables and parameters

imity to LTER sites was one factor considered in selecting NEON sites. Hence, cross-network syntheses with LTER were envisioned from the beginning of NEON. Both LTER and NEON address issues of broad social relevance. Social science is not a core area of LTER (J. A. Jones & Nelson, 2020), but social-ecological systems and related questions (e.g., S. L. Collins et al., 2011) are central to many LTER programs. Consideration of social-ecological systems motivated the selection of many of the variables measured by NEON, such as disease-transmitting organisms, that are not consistently measured at LTER sites. Social and economic factors also are central to international LTERs (Mirtl et al., 2018).

3. Goals and Approaches for Cross-Network Synthesis Efforts

Cross-network synthesis efforts are needed, and can be very powerful, because of the insights they provide. Goals for such syntheses include: generalize patterns and processes among locations, identify interactions among ecological processes at one or multiple sites, generalize across temporal scales, reveal differences among methods, or test the potential and limitations of models (Table 2). One form of synthesis tests the generality of a finding (or concept or hypothesis) about a single property or process across sites (Type 1, Table 2). Examples include how C flux varies among locations in the AmeriFlux network (Novick et al., 2018); how atmospheric deposition varies among locations in the NADP network (Lajtha & Jones, 2013); how streamflow trends vary among locations in the USGS NWIS (Lins & Slack, 1999); or how climate trends vary among locations in the US Historical Climatology Network (USHCN) (Menne et al., 2018). Type 1 synthesis spans the geographic coverage of the networks. For example, the 28 LTER sites and the 47 NEON sites are distributed throughout the United States and LTER sites also occur in Antarctica and the Pacific (Figure 2).

Analysis of multiple data streams can produce a more complete or nuanced understanding of a phenomenon or opportunities to test hypotheses using independent datasets. A second type of synthesis, “multiple properties or processes within a site,” aims to elucidate interactions among ecological processes using data on multiple complementary properties or processes at a site (Type 2, Table 2). Long-term mechanistic experiments (e.g., from LTER) provide insights for interpreting monitoring data (e.g., from NEON) at a site. Examples include how long-term manipulations of vegetation influence C exchange, or how an invasive insect affects ecosystem water exchange (Giasson et al., 2013; Kim et al., 2017). Type 2 synthesis studies could be based on complementary measurements from multiple networks. Many opportunities for Type 2 synthesis exist at sites which are “co-located” (participate in) both the LTER and NEON networks (Figure 2, Table S1).

Analyses of multiple data streams from different networks could contribute to more general understanding of patterns and trends at regional to continental scales over the long term. A third approach to synthesis, “multiple properties or processes across sites” (Type 3, Table 2) seeks generalizations about interactions among ecological processes at many locations. For example, long-term experiments at multiple locations provide insights for interpreting monitoring data within or among biomes or ecosystem types, such as how vegetation manipulations affect streamflow in multiple different forest ecosystems (J. A. Jones & Post, 2004), or how climate change is affecting ecosystem water use (J. A. Jones et al., 2012). Type 3 synthesis studies could be based on complementary measurements from the nine co-located sites in LTER and NEON (italicized in Table S1, Figures 2 and 3a), grouped by biome or ecosystem type, or across all sites in the two networks, which span much of the range of mean annual precipitation and temperature in North America (Figure 3b) (Villarreal et al., 2018).

Additional forms of synthesis among research and monitoring networks include syntheses across scales, across methodological approaches, and using modeling (Table 2). Syntheses across scales (Type 4) build on data collected at more than one temporal scale to elucidate temporal patterns in ecological processes, including trends, cycles, and thresholds. For example, long-term datasets and experiments at research networks such as LTER complement short-term, high-resolution data from NEON or other monitoring networks. Syntheses that compare methods (Type 5) can reveal differences in ecological patterns that result from disparate measurement approaches. Different types of data pertaining to a single phenomenon permit comparisons among multiple modes of observation. Model syntheses (Type 6) combine data from mechanistic experiments and monitoring to inform and constrain models, to understand uncertainty in projections, and to identify needs for model improvements.

4. Opportunities for Cross-Network Synthesis Studies Linking LTER and NEON

We provide examples of potential cross-network synthesis studies that can accelerate environmental science by linking the five core areas of long-term research (in LTER) with the five main measurement programs (of NEON) (Figure 1). These examples comprise six broad research areas: (1) ecosystem fluxes of C and energy; (2) remote sensing and ecosystem models; (3) aquatic-terrestrial linkages; (4) soil biogeochemical and mi-

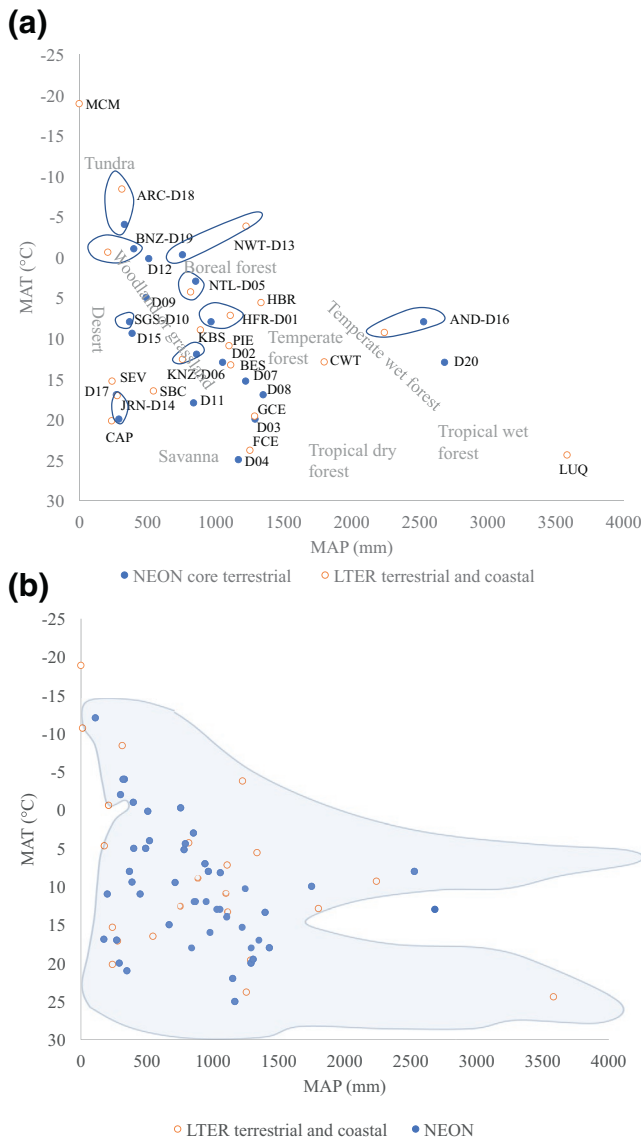


Figure 3. Climate overlap and coverage of NEON and LTER networks. (a) Mean annual temperature (MAT) and precipitation (MAP) for LTER sites and core terrestrial NEON sites, oriented in Whittaker biome space. A total of nine LTER sites are co-located with NEON sites: seven (ARC, BNZ, HFR, KNZ, NTL, NWT, SGS) are co-located with core terrestrial NEON sites, and two (AND, JRN) are co-located with noncore NEON sites. The three-letter acronyms for LTER sites and the D01 notation for NEON domains are defined in Table S1. Climate data from co-located sites are enclosed within circles. Co-located sites may have slightly different climate values because climate varies within each domain, and climate data may have been obtained from different meteorological stations and/or for different time periods (see Table S1). Source (J. A. Jones et al 2012; NEON data from Cove Sturtevant.) (b) Mean annual temperature and precipitation for LTER sites and all NEON sites (core terrestrial, core aquatic, noncore terrestrial, noncore aquatic). Outline is range of MAP and MAT in North America, adapted from Novick et al. (2018). Solid dot outside of polygon in middle right is NEON domain 20 (Hawaii); open circles outside of polygon in upper left corner are Antarctic LTER sites.

Table 3

Examples of Ongoing Type 2 (Multiple Properties or Processes, Within Site) Synthesis Research Questions Linking Long-Term Experiments and Observations From the LTER Research Network With Eddy Flux Tower Measurements in LTER and the NEON Monitoring Network

Biome	Research question	LTER site	NEON site
Arctic tundra	How land cover and fire disturbance affect net ecosystem exchange	Arctic (ARC)	Toolik (TOOL)
Boreal forest	How upland versus lowland landscape position and varying permafrost affect C fluxes	Bonanza Creek (BNZ)	Caribou Creek (BONA)
Temperate forest	How various historic land uses and invasive insects affect C exchange (Figure 4)	Harvard Forest (HFR)	Harvard Forest (HARV)
Desert	How vegetation and landforms affect spatial variability in water and energy fluxes	Jornada (JRN)	Jornada (JORN)
Tallgrass prairie	How experimental fire regimes and grazing affect C exchange (Figure 5)	Konza (KNZ)	Konza (KONZ)
Temperate forest-lake	How aquatic ecosystems affect terrestrial C exchange	North Temperate Lakes (NTL)	UNDERC (UNDE)
Alpine tundra	How fine scale heterogeneity in topographically complex terrain affects C exchange	Niwot Ridge (NWT)	Niwot Ridge (NIWO)

Note. Details of eddy flux tower locations and relevant publications are in Table S3.

crobial dynamics; (5) organism and species distribution models; and (6) land use and disturbance history, resilience and stability (Figure 1). A key theme in all these examples is how synergies emerge from the interaction of LTER hypothesis-based, mechanistic science interacting with NEON standardized, spatially distributed monitoring.

4.1. Ecosystem Fluxes of Carbon, Energy and Water

Complementarities among research and monitoring networks can address broad questions about C cycling at regional and continental scales (Figure 1). Long-term experiments and observational studies have documented multidecade changes in ecosystem C storage, and the mechanisms underlying these changes. These experiments and studies complement high-resolution information on C exchange from eddy flux towers. In the Arctic tundra and boreal forest (LTER sites in Alaska), warming climate has reduced soil C stocks (Euskirchen et al., 2017). In the desert (Sevilleta LTER), vegetation change from grassland to shrubland increased C sequestration (Petrie et al., 2015). In freshwater marsh and mangrove forests (Florida Everglades LTER), C sequestration depended on vegetation type, temperature, and flooding (Malone et al., 2016). In a temperate freshwater marsh (Plum Island LTER), increased rainfall reduced soil salinity thereby increasing productivity and C (Forbrich et al., 2018). In an urban site (Phoenix LTER), outdoor water use increased evapotranspiration as well as C storage (Templeton et al., 2018). There is great potential synergy between these experiments and networks of eddy covariance flux towers that provide continuous measurements of carbon dioxide (CO₂), water vapor, and energy fluxes that are used to estimate ecosystem productivity and water and C exchange between ecosystems and the atmosphere (Campioli et al., 2016). The global network of eddy flux towers (e.g., AmeriFlux, Fluxnet) (Novick et al., 2018) includes 40 flux towers at LTER sites, and NEON has added a flux tower at each of the 47 NEON sites; data from the NEON towers are shared with AmeriFlux and FLUXNET (Metzger et al., 2019).

Syntheses of ecosystem experiments and observations from LTER research with monitoring data from NEON and other networks can reveal interactions among factors influencing C and energy fluxes, characterize variability, and guide efforts to scale estimates of ecosystem C exchange (Table 3). For example, in northern temperate forest (the Harvard Forest LTER and NEON site), combining data from long-term experiments on vegetation manipulation from LTER with information from multiple eddy flux towers (Type 2 synthesis) revealed how soil respiration varied with weather, phenology, invasive insects, forest management practices, and atmospheric N deposition over 22 years (Giasson et al., 2013). In another example, long-term monitoring of vegetation and streamflow from LTER was combined with data from flux towers to show how invasive insect outbreaks reduced leaf area and increased water yield at the Harvard Forest (Kim et al., 2017).

Going forward, there is great potential for testing general hypotheses by combining information from LTER long-term experiments or observations with data from multiple eddy flux towers maintained by NEON, LTER, or other networks, which replicate measurement conditions or sample local variation in vegetation or landform conditions (Table 3). Examples include how past fire severity affects C flux in the Arctic tundra (Rocha & Shaver, 2011); how various permafrost conditions affect C flux response to climate warming in the boreal forest (Bonanza Creek) (Euskirchen et al., 2014); and how various land use histories or insect invasions affect C exchange (Harvard Forest, Figure 4). Moreover, such studies could show how local variation in soil temperature, water table fluctuations, and plant activity (measured by LTER and NEON) affect C flux (measured at eddy flux towers in NEON, LTER, and other networks) (e.g., Sturtevant et al., 2016). Combining information from multiple towers at a site can assist efforts to scale up eddy fluxes for modeling (Xu et al., 2017) (Table 3, Table S3).

In the future, Type 3 (multiple properties or processes across sites) syntheses could contribute to more general understanding of C and water exchange over the long term (Figure 1). For example, Type 3 syntheses could combine long-term observations of vegetation and climate at LTER sites with data from eddy flux towers to test hypotheses about how trends in winter precipitation influence C uptake in warm desert shrublands (e.g., Biederman et al., 2018). Type 6 (models) syntheses could combine results from long-term experiments and observations at LTER sites with data on C exchange from eddy covariance sites from NEON, LTER, and AmeriFlux in order to test hypotheses linking rising atmospheric CO₂, plant functional traits and forest structure, and ecosystem water use efficiency in forests (e.g., Mastrotheodoros et al., 2017). Type 4 (across temporal scales) and Type 6 (models) syntheses also could combine data from long-term experiments and monitoring with shorter-term eddy flux data in models to predict the response of net ecosystem exchange to long-term ecosystem change (e.g., Wright & Rocha, 2018).

4.2. Remote Sensing and Ecosystem Models

Several forms of synthesis could combine long-term field data from LTER with lidar and hyperspectral data from NEON to assess how land cover change and vegetation dynamics influence ecosystem processes (Figure 1). Each year, the NEON Airborne Observing Platform (AOP) obtains acquires lidar (Light Detection and Ranging) and imaging spectrometer data with a nominal spatial resolution of 1–2 m², and 0.25 m resolution digital orthophotos for hundreds of square kilometers surrounding each NEON site (Figure 2). Data are made available at various postprocessing levels and include topography, vegetation structure, and canopy physical and chemical properties.

Initial efforts have used field data in combination with NEON airborne mapping products to improve remote-sensing based vegetation classifications (e.g., Scholl et al., 2020), infer structures that may influence ecosystem function (LaRue et al., 2019), or to map biodiversity patterns that are difficult to assess from field data (Hakkenberg et al., 2018; Musavi et al., 2017). Type 2 (multiple properties or processes within sites) and Type 3 (multiple properties or processes across sites) syntheses could combine field data from LTER with NEON remotely sensed data to explore how landforms influence disturbance, climate, and vegetation dynamics (e.g., Antonarakis et al., 2014; S. J. Frey et al., 2016; Yousefi Lalimi et al., 2017). Repeat NEON mapping using hyperspectral imagery may reveal ecosystem responses, such as plant water stress (e.g., Brodrick & Asner, 2017), that correspond with long-term trends in vegetation measurements from LTER. Type 2 or type 3 syntheses also could combine long-term data on vegetation from LTER sites with analyses of NEON's laser scanning and imaging spectroscopy to examine how ecosystem changes are related to plant functional traits such as foliage height diversity, leaf chlorophyll and water content (e.g., Schneider et al., 2017) or plant biomass (Goulden et al., 2017).

Type 6 syntheses (models) have used NEON eco-climate domain polygons as the basis for efforts to extrapolate ecosystem processes across regions. For example, Iwema et al. (2017) used data from the AmeriFlux network to examine how soil moisture measurements in eight NEON domains influenced surface energy flux parameters in a land surface model. Swann et al. (2018) used the Community Earth Systems model to test how simulated forest loss in 13 forested NEON eco-climatic domains altered climate dynamics, transpiration, and primary productivity in other NEON domains.

Going forward, Type 6 synthesis (models) have great potential to be used in conjunction with LTER and NEON data to develop continental-scale projections. For example, Liu et al. (2018) used gridded remote-

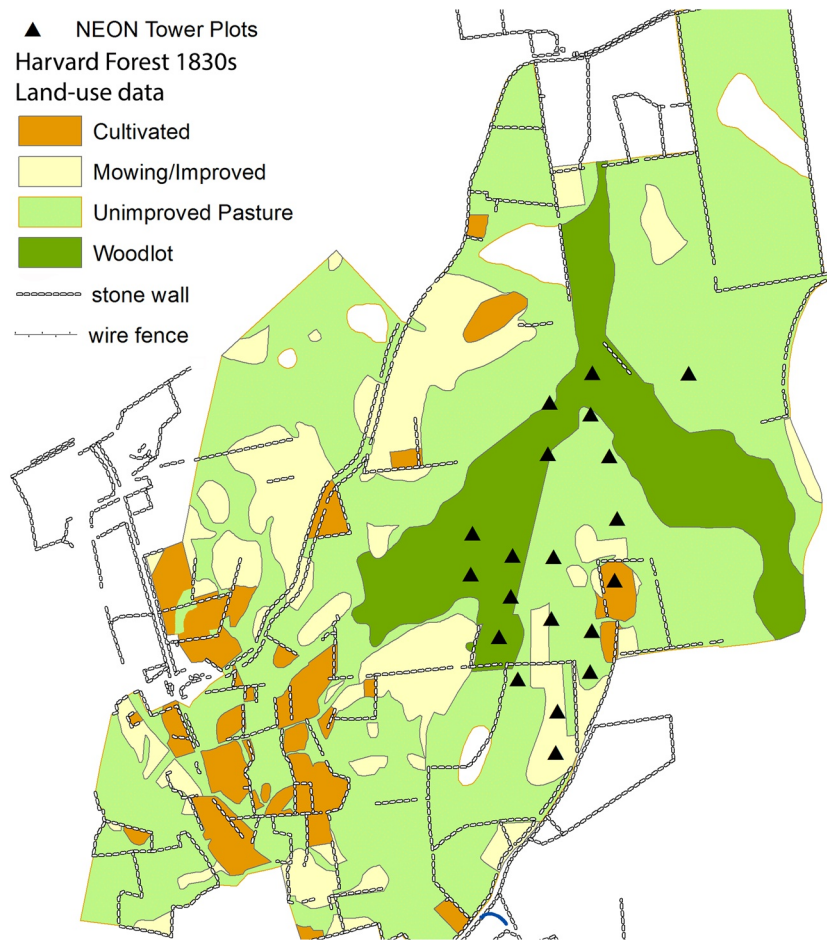


Figure 4. Long-term LTER-based research and NEON sampling are co-located across multiple land use histories at the Harvard Forest (Type 2 synthesis). LTER retrospective studies of land use at the Harvard Forest indicate that the contemporary forest has been shaped by several hundred years of land use. Detailed studies of ownership deeds, stonewalls, barbed wire fences, and soil plow horizons reveal spatial and temporal patterns of cultivation, pasture, forest harvest and woodlot management since 1730 (Foster, 1992). NEON sampling points are arrayed across the entire Harvard Forest site to document broad-scale patterns. Thus, plots surrounding the eddy flux tower are located in areas that have been exposed to different combinations of land use histories (black triangles in figure). These historic land uses alter carbon distribution in soil profiles and soil respiration (Giasson et al., 2013) in ways that affect carbon exchange, which is measured by the NEON flux tower. These ongoing type 2 efforts (multiple properties or processes, within site) demonstrate the potential for co-location of LTER land use history studies and NEON sampling to reveal novel results of LTER long-term studies, while concurrent LTER data collection and complementary experiments provide mechanistic explanations and context for interpreting responses to contrasting land-use histories. Going forward, such studies could be pursued at any site where current short-term measurements and land-use history are available.

ly sensed data products and data from an eddy flux tower network (FLUXNET) to calculate spatial and temporal sensitivity of GPP and total ecosystem respiration to temperature and precipitation in 17 NEON eco-climatic domains. In addition, information from the NEON AOP could be used to track albedo and vegetation phenology dynamics near eddy flux towers (e.g., Wang et al., 2017) in combination with long-term vegetation observations to elucidate factors affecting ecosystem exchange.

4.3. Aquatic – Terrestrial Linkages

Combining long-term experiments and observations from LTER with data provided by NEON could improve whole-catchment C and nutrient budgets (Figure 1). Although they occupy small areas, aquatic ecosystems can make a disproportionately large contribution to terrestrial C storage in some regions (Buffam et al., 2011), and rivers export a significant fraction of terrestrial net ecosystem production in

Table 4

Examples of Potential Future Synthesis Opportunities to Characterize Whole-Watershed Elemental Budgets and Examine Interactions Between Aquatic and Terrestrial Ecosystem Processes by Combining Aquatic Studies with Eddy Flux Tower and Other Measurements at Sites That are Co-located in LTER (Research Network) and NEON (Monitoring Network)

Biome	LTER site name	NEON aquatic site	NEON terrestrial site
Arctic tundra	Arctic (ARC)	Oksrukuyik Creek (OKSR)	Toolik (TOOL)
Temperate forest	Baltimore (BES)	Posey Creek (POSE)	Blandy Experimental Farm (BLAN)
Boreal forest	Bonanza (BNZ)*	Caribou Creek (CARI)	Caribou-Poker Flats watershed (BONA)
Savanna	Georgia Coastal Ecosystem (GCE)	Barco Lake, Suggs Lake (BARC, SUGG)	Ordway-Swisher Biological Station (OSBS)
Grassland	Konza (KNZ)*	Kings Creek (KING)	Konza Prairie Biological Station (KONZ)
Alpine tundra	Niwot Ridge (NWT)	Como Creek (COMO)	Niwot Ridge (NIWO)

Note. See details of site locations and instrumentation in Table S4. LTER sites marked with asterisk are located in the same watershed as the NEON sites.

the U.S. each year (Butman et al., 2016). However, spatial variability of C storage and transport is high (Argerich et al., 2016) and strongly linked to terrestrial processes (McCullough et al., 2018), including past disturbance (Lajtha & Jones, 2018; Meyer et al., 2014). Terrestrial ecosystem processes also influence spatial and temporal variation in N export from streams (Beaulieu et al., 2015; Neilson et al., 2018; Webster et al., 2019). Improved integration of ecosystem properties linking terrestrial and aquatic ecosystems would more accurately reflect C and nutrient budgets at scales relevant to Earth system models (Wollheim et al., 2018).

In the future, Type 3 (multiple properties or processes across sites) analysis of linked aquatic-terrestrial dynamics could link aquatic and terrestrial installations at NEON sites, some of which are co-located with LTER (or other network) eddy flux towers (Table 4, Table S4). Combined terrestrial and aquatic measurements have helped to estimate how changes in C loading may also influence N and P in lakes (Corman et al., 2018) or how N and P loading influence C dynamics in streams (Mutschlechner et al., 2018). They have shown how fire and grazing influence inorganic nutrient dynamics of streams (P. L. Sullivan et al., 2019), or how ecosystems process N deposition (Litaor et al., 2018). Fluorescence measurements of dissolved organic matter have helped discriminate land use and climate effects on the chemistry of exported DOC at the Andrews Forest LTER in Oregon (e.g., Lee & Lajtha, 2016); fluorescent DOC measured at many NEON sites could be used in future syntheses linking multiple sites. At the North Temperate Lakes LTER in Wisconsin, the contribution of lakes to total CO₂ flux can be estimated by combining LTER lake metabolism and CO₂ data and models with terrestrial flux estimates from a nearby NEON terrestrial flux tower (Table 3). Combined NEON and LTER installations will facilitate estimates of allochthonous and autochthonous sources of C in aquatic ecosystems (Hanson et al., 2016), which are essential to constructing C budgets at regional to continental scales.

Integration of NEON with LTER and other networks might also advance understanding and prediction of N fluxes at continental scales. For example, Type 3 studies could use NEON and LTER data to test how vegetation cover and phenology from remotely sensed imagery are related to stream N fluxes in various biomes (Table 4). Trends and fluxes of N in precipitation or streams that have been described for various networks (e.g., Argerich et al., 2013; Lajtha & Jones, 2013) could be combined in Type 3 (multiple properties or processes across sites) studies with aquatic N data from NEON aquatic sites and N content of plant canopies in those watersheds, estimated from hyperspectral data collected by the NEON AOP.

4.4. Soil Biogeochemical and Microbial Dynamics

Many opportunities exist to combine long-term studies from LTER with soil measurements from NEON to better understand how soil biogeochemistry and microbial processes drive ecosystem response to environmental change (Figure 1). Long-term experiments on soil N additions, soil warming, and soil detrital additions and removals have been conducted at many locations, including LTER sites. NEON samples biogeochemical stocks and soil N processes, microbial community composition and biomass, and vegetation one to three times per year at 5-year intervals at multiple plots in each NEON site (Hinckley et al., 2016b).

Type 2 (multiple properties or processes within sites) and Type 3 (multiple properties or processes across sites) synthesis efforts could inform our understanding of drivers of microbial abundance, diversity, and community composition; organic matter and nutrient cycling dynamics; and C stabilization and N transformations across different ecosystems. For example, long-term experiments have shown that despite strong compositional differences across sites, microbial communities shifted in a consistent manner in response to N or P additions (Leff et al., 2015) as well as climate variability and soil C content (Delgado-Baquerizo et al., 2016). Type 2 and Type 3 syntheses could link long-term experiments at LTER sites to data on microbial populations, climate, and nutrient fluxes from NEON sites to examine hypotheses about how microbial dynamics mediate biogeochemical fluxes.

In addition, new syntheses could improve predictions of which systems are most vulnerable to C and nutrient loss at regional to global scales. A long-term experiment showed that two decades of elevated nitrogen inputs increased forest soil C, largely due to a suppression of organic matter decomposition (S. D. Frey et al., 2014). Type 3 syntheses could link the findings from long-term soil nutrient addition experiments and soil warming experiments to soil surveys and distributed NEON data (e.g., soil C and N concentrations and stocks) to predict soil C and N sinks and sources at the continental to global scales (e.g., Crowther et al., 2016; Wieder et al., 2015).

LTER studies also have shown that soil C and N responses to long-term warming and nutrient additions vary seasonally (Contosta et al., 2011) and may continue to change over multiple decades (Melillo et al., 2017; Reich et al., 2018). Type 2 syntheses could enhance understanding of soil N response to environmental change by combining long-term experiments and observations of effects of atmospheric N deposition, windthrow, fire, grazing, and other changes at LTER sites with NEON observations of soil properties at those sites (Figure 1). Type 6 syntheses (models) could use ecosystem models that combine long-term data on atmospheric deposition from NADP (Lajtha & Jones, 2013; T. J. Sullivan et al., 2018) with NEON's standardized N mineralization data to predict and interpret effects of air pollution on soil ecosystem processes.

4.5. Animals and Species Distribution Models

Syntheses linking long-term observations and experiments from LTER with data from NEON can provide insights into population and species responses to environmental change (Figure 1). Long-term observational studies reveal how populations and communities respond to land use, disturbance, and climate. NEON provides data on microbial communities, aquatic and terrestrial plants, breeding birds, and fish, as well as focal species of small mammals and insects. NEON is also analyzing eDNA (i.e., organism DNA in the environment) in aquatic ecosystems. Environmental DNA has great potential for monitoring common species and to detect and identify the presence of many species (Bohmann et al., 2014).

Synthesis of new data from NEON with long-term studies can address key questions in biodiversity, population dynamics, species distribution models, and metacommunity dynamics. For instance, long-term studies at Harvard Forest LTER in Massachusetts have shown that small mammal community structure is relatively unaffected by species invasion (e.g., of hemlock woolly adelgid) or disturbance (e.g., experimental mortality of hemlock) (Degrassi, 2018). Spatial analyses of small mammal data across the continental United States (from NEON) indicated that body size variation and mammal species richness were positively associated with temperature (Read et al., 2018). Type 2 or Type 3 synthesis efforts could combine results of long-term experiments from LTER showing mechanistic organism response to invasion or disturbance with data from NEON sampling of small mammals to examine how climate change, disturbance, and invasion processes are affecting mammal populations at local or continental scales. For example, at the Konza Prairie in Kansas, NEON small mammal and tick survey plots are located in areas where fire and grazing have been manipulated in LTER long-term experiments, potentially revealing how small mammal and tick populations respond to disturbances (Figure 5). The co-location of LTER experiments and NEON sampling enable NEON data to reveal novel results of LTER long-term experiments, while concurrent LTER data collection and complementary experiments provide mechanistic explanations and context for interpreting species data from monitoring networks.

Type 2 (multiple properties or processes within sites) and Type 3 (multiple properties or processes across sites) syntheses also can unravel underlying causal mechanisms linking long-term fish popu-

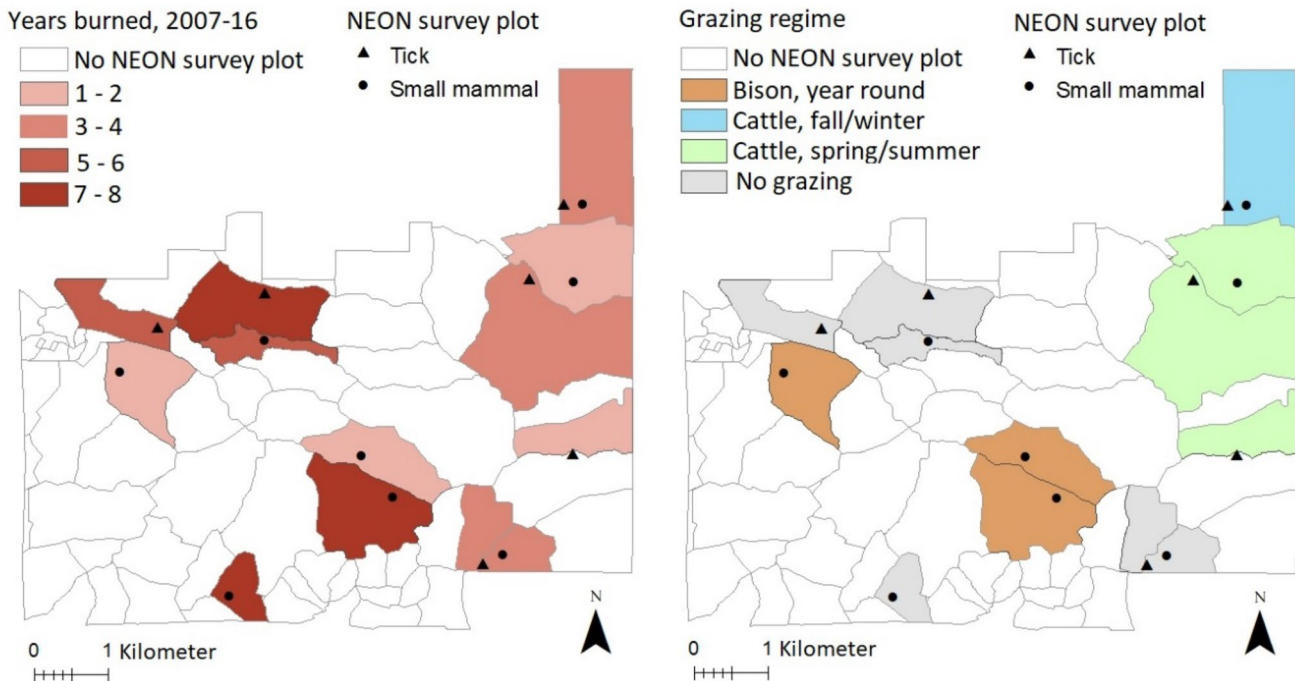


Figure 5. Long-term LTER-based research and NEON sampling are co-located across multiple fire and grazing treatments at the Konza Prairie Biological Station. LTER sampling at Konza Prairie is designed to document a suite of ecological responses to specific combinations of prescribed fire and grazing treatments, which also represent a range of potential land-use and land-cover scenarios for the region. In contrast, NEON sampling points are arrayed across the entire Konza Prairie site to document broad-scale patterns. As a result, NEON small mammal and tick survey plots are located in areas that have been exposed to different combinations of experimental burning frequency (left figure) and grazing by bison or cattle (right figure) as part of LTER long-term experiments. These treatments alter vegetation composition and structure in ways that affect both small mammal and tick populations (Cully, 1999; Matlack et al., 2008). In ongoing studies, the co-location of LTER experiments and NEON sampling enable NEON data to reveal novel results of LTER long-term experiments, while concurrent LTER data collection and complementary experiments will provide mechanistic explanations and context for interpreting responses to contrasting land-use practices.

lation responses to environmental change by combining systematic fish surveys and eDNA measurements in aquatic systems conducted by NEON to results from long-term experiments and observations. Long-term studies at LTER sites have documented native fish population responses to invasive fish species (Hansen et al., 2017), to climate and trophic interactions (Parks & Rypel, 2018), and to disturbance and vegetation change (Dodds et al., 2012). Initial studies indicate that eDNA can be used in conjunction with long-term monitoring of fish populations in lakes (Klobucar et al., 2017). Given the high variance of many aquatic populations over time (e.g., Batt et al., 2017), Type 2 (multiple properties or processes at a site) or Type 6 (model) syntheses that combine NEON data on both fish population dynamics and physicochemical conditions within lakes and streams with LTER and other long-term studies of streams and lakes will help reduce uncertainty in population models and causes of population change in fish.

Several forms of synthesis efforts also could contribute to species distribution models (Figure 1). NEON is collecting systematic data on focal taxa, including soil microbes; ticks, mosquitoes, and ground beetles; small mammals; and breeding birds (Egli et al., 2020; Springer et al., 2016; Thorpe et al., 2016). LTER studies have documented long-term trends and constructed models for species distributions of birds (Betts et al., 2018), arthropods (Lister & Garcia, 2018), and invasive insects (Schliep et al., 2018). Long-term experiments and observational studies also document community level responses, for example, to species loss (e.g., hemlock removal, Record et al., 2018) or disturbance (e.g., saltwater intrusion, Zhai et al., 2016). NEON data are being used to model spatial patterns of tick abundance (Klarenberg & Wisely, 2019). Data from long-term experiments and observations have been used to test ecological theory and improve models of species distribution and dynamics (e.g., Snell Taylor et al., 2018; Thomas Clark et al., 2018). Going forward, synthesis studies could combine results from long-term experiments at LTER sites with measurements of species

across the NEON network to draw inferences about general factors influencing species distributions (Type 3) and to identify knowledge gaps in models of species distributions (Type 6).

4.6. Disturbance History, Stability and Resilience

Combining theory, long-term experiments, and observations of disturbances from LTER with high-frequency data provided by NEON can provide insights and generalizations about ecosystem response to disturbance, stability and resilience (Figure 1). Long-term studies demonstrate how land use legacies and disturbance history shape modern-day landscape patterns and ecological communities (Acker et al., 2017). Data from NEON, including flux towers, remote sensing, aquatic, soil, and organism sampling, provide information on current ecosystem status. The combination of long-term experiments and observations from LTER on land use history and disturbance could provide context for understanding monitoring data from NEON on ecosystem fluxes (Figure 4) and species distributions and abundance (Figure 5).

Long-term studies have documented alternative stable states and associated mechanisms, but records may be insufficient to test for regime shifts (Bestelmeyer et al., 2011; Ratajczak et al., 2014; Yu et al., 2019), because detection of their approach and validation of the change in feedbacks that accompany regime shifts require unbroken series of frequent observations sustained for long periods of time (Butitta et al., 2017). LTER-developed theory (e.g., Adam et al., 2011; Bestelmeyer et al., 2013; Chapin et al., 2010) provides a framework for combining long-term data from LTER with high-resolution NEON data to gain insight into ecosystem resilience. In aquatic systems, NEON will collect high-frequency (subhourly) measurements of several variables including nitrate, dissolved organic matter, and conductivity. Type 4 syntheses (across temporal scales) of NEON data combined with LTER data and understanding of ecosystem states could help test a key hypothesis that changes in the variance of biogeochemical fluxes (P, N, and C) may reveal regime shifts in ecosystems (e.g., Webster et al., 2016) (Figure 1).

In summary, many examples exist of ongoing synthesis between the LTER research network and the NEON monitoring network, but these are mostly Type 2 (multiple properties or processes within sites) syntheses based at sites that are co-located in both networks. While a great many studies have been published describing the potential for LTER-NEON syntheses, very few studies have been published that report results of such syntheses. Moreover, there is a dearth of studies that utilize the many other potential types of synthesis, including Type 3 (multiple properties or processes across sites), Type 4 (across temporal scales), Type 5 (across methodological approaches), and Type 6 (models) syntheses. Nevertheless, as described above, ongoing studies provide exciting potentials for specific research questions that could be explored using these varied synthesis approaches.

5. Conclusions

In this era of rapid, broad-scale environmental change, publicly available information from complementary environmental science research networks, such as LTER, and monitoring networks such as NEON offer opportunities for discovery, arising from the potentials for LTER measurements, experiments, models, and observational studies to provide context and mechanisms for interpreting NEON data, and for NEON measurements to provide standardization and broad scale coverage that complement LTER studies. Many different types of cross-network synthesis are possible, in six broad areas of ecology. To date, cross-network efforts are addressing topics including how long-term vegetation change influences C fluxes; vegetation structure and function revealed by detailed remote sensing; aquatic-terrestrial connections of nutrient cycling linking vegetation to streams and lakes; effects of soil biogeochemistry and microbial processes on ecosystem response; population and species responses to environmental change; and ecosystem response to disturbance, stability and resilience. Current efforts focus primarily on synthesis of properties and processes at individual sites where NEON and LTER are co-located, but they could be extended in ways described in this study to address broader questions in ecology and environmental science, at a wider range of sites. These potential syntheses also provide a pathway for the broader scientific community, beyond LTER and NEON, to participate in cross-network research. These findings apply to cross-network syntheses among other research and monitoring networks in the US and globally, and can guide scientists and research administrators in promoting broad-scale research that supports resource management and environmental

policy. The emergence of these synergies should also help to make long term research networks and sites more open to new investigators as they will facilitate the flow of information and ideas and the development of new collaborations. This flow, and the links to resource management and policy, could also contribute to broadening participation of groups traditionally underrepresented in science.

Data Availability Statement

Data were not used, nor created for this research.

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