esa

ECOSPHERE

SYNTHESIS & INTEGRATION

Taking the pulse of a continent: expanding site-based research infrastructure for regional- to continental-scale ecology

Debra P. C. Peters,[1,3,†] Henry W. Loescher,[2] Michael D. SanClements,[2] and Kris M. Havstad[1]

[1]*United States Department of Agriculture, Agricultural Research Service,*
Jornada Experimental Range and Jornada Basin Long-Term Ecological Research Program, Box 30003, MSC 3JER,
New Mexico State University, Las Cruces, New Mexico 88003 USA
[2]*National Ecological Observatory Network and Institute of Alpine and Arctic Research, University of Colorado,*
Boulder, Colorado 80301 USA

Citation: Peters, D. P. C., H. W. Loescher, M. D. SanClements, and K. M. Havstad. 2014. Taking the pulse of a continent: expanding site-based research infrastructure for regional- to continental-scale ecology. Ecosphere 5(3):29. http://dx.doi.org/10.1890/ES13-00295.1

Abstract. Many of the most dramatic and surprising effects of global change on ecological systems will occur across large spatial extents, from regions to continents. Multiple ecosystem types will be impacted across a range of interacting spatial and temporal scales. The ability of ecologists to understand and predict these dynamics depends, in large part, on existing site-based research infrastructures developed in response to historic events. Here we review how unevenly prepared ecologists are, and more generally, ecology is as a discipline, to address regional- to continental-scale questions given these pre-existing site-based capacities, and we describe the changes that will be needed to pursue these broad-scale questions in the future. We first review the types of approaches commonly used to address questions at broad scales, and identify the research, cyber-infrastructure, and cultural challenges associated with these approaches. These challenges include developing a mechanistic understanding of the drivers and responses of ecosystem dynamics across a large, diverse geographic extent where measurements of fluxes or flows of materials, energy or information across levels of biological organization or spatial units are needed. The diversity of methods, sampling protocols, and data acquisition technologies make post-hoc comparisons of ecosystems challenging, and data collected using standardized methods across sites require coordination and teamwork. Sharing of data and analytics to create derived data products are needed for multi-site studies, but this level of collaboration is not part of the current ecological culture. We then discuss the strengths and limitations of current site-based research infrastructures in meeting these challenges, and describe a path forward for regional- to continental-scale ecological research that integrates existing infrastructures with emerging and potentially new technologies to more effectively address broad-scale questions. This new research infrastructure will be instrumental in developing an "über network" to allow users to seamlessly identify and select, analyze, and interpret data from sites regardless of network affiliation, funding agency, or political affinity, to cover the spatial variability and extent of regional-to continental-scale questions. Ultimately, scientists must network across institutional boundaries in order to tap and expand these existing network infrastructures before these investments can address critical broad-scale research questions and needs.

Key words: connectivity; cyber-infrastructure; data interoperability; ecological culture; ecological networks; macro-ecology; open science.

Received 20 September 2013; revised 20 January 2014; accepted 27 January 2014; final version received 25 February 2014; **published** 17 March 2014. Corresponding Editor: S. L. Collins.

[3] Present address: United States Department of Agriculture, Office of the Chief Scientist, Washington, D.C. 20250 USA.
† **E-mail:** debpeter@nmsu.edu

INTRODUCTION

Across much of the central North American continent in the 1930s, scientists were engaged in fine-scale studies of changes in grass cover during a decade-long drought (Albertson and Weaver 1942). Although scientists recognized that grass mortality occurred at the scale of 1-m^2 quadrats (Weaver and Albertson 1936; Fig. 1A), their research was unconnected to the degradation occurring on vast expanses of abandoned agricultural land located throughout the region (Worster 1979). These landscapes were highly susceptible to erosion by wind and water that compounded the devastation of the prolonged drought (Schubert et al. 2004). The spatial connectivity across these landscapes led to the development and propagation of massive dust storms across the continent in a multi-year event termed the "Dust Bowl" (Fig. 1B, C) (Peters et al. 2004*a*). Soil particles and dust storms from the Central U.S. were documented in a number of cities along the East Coast of the continent (Mattice 1935). Emergent properties from these land surface-atmosphere interactions had a domino effect on other ecosystem processes, including landscape- to regional-scale outbreaks of pests and pathogens, and losses of soil nutrients. Regional to continental-scale food shortages, and decreased air and water quality had consequences for human health and well-being, the economy, and human and animal migration (Chepil 1957, Egan 2006).

Although the Dust Bowl was a unique phenomenon in the history of the U.S. in terms of the extent, degree, and types of devastation (Herweiger et al. 2006), changes in climate and land use driven by global environmental change have the potential to increase the frequency and intensity of similar regional- to continental-scale events. For example: (1) the recent severe drought (2011) influenced more than two-thirds of the continental U.S., most of Mexico, and parts of Canada (Fig. 2) and reflects the more arid conditions expected in the future (Seager et al. 2007), (2) the mosaic of land use types across all continents (except Antarctica), increasingly includes urban, suburban, protected, and degraded areas with high connectivity by wind, temperature, and water that lead to the regional- to continental-scale generation of heat islands, dust storms, runoff of water, soil, and nutrients, and spread of invasive species (Lehner et al. 2006, Gill et al. 2010, Choobari et al. 2014), (3) at the global scale, coupled climatic-ecological events can connect continents via air masses and ocean currents with localized effects on human health, well-being, and security as well as feedbacks to the climate system (Perry et al. 1997, Yoshioka et al. 2007, National Climate Assessment 2011, President's Council of Advisors on Science and Technology 2011, IPCC 2012, Creamean et al. 2013).

These broad-scale events highlight the urgent need to understand the spatial and temporal linkages among regional- to continental-scale ecological dynamics and changes in climate, land use, and the biota at finer scales (Trenberth et al. 2007). However, similar to the 1930s, most process-based ecological research is still conducted at the scale of small research plots (e.g., Knapp et al. 2012), and is typically not designed to address dynamics across broad spatial extents. Over the past few decades, ecologists have increased the spatial extent of studies to include patterns and processes needed to understand landscapes (e.g., Jones et al. 2012), and networks of geographically distributed sites have emerged as important entities to examine regional- to continental- and global-scale phenomena (Peters et al. 2008, Robertson et al. 2012). In most cases, research plots within sites that are part of one or more organized networks remain the focal units of study (e.g., Fountain et al. 2012) (Fig. 3). Given this focus, critical questions remain: how prepared are ecologists to provide the understanding and tools needed to either avoid or adapt to the consequences of regional- to continental-scale events with potentially catastrophic ecological impacts (e.g., the next Dust Bowl, Superstorm 'Sandy', Asian dust storms, Australian wildfires, Sumatra earthquakes and tsunamis)? How can

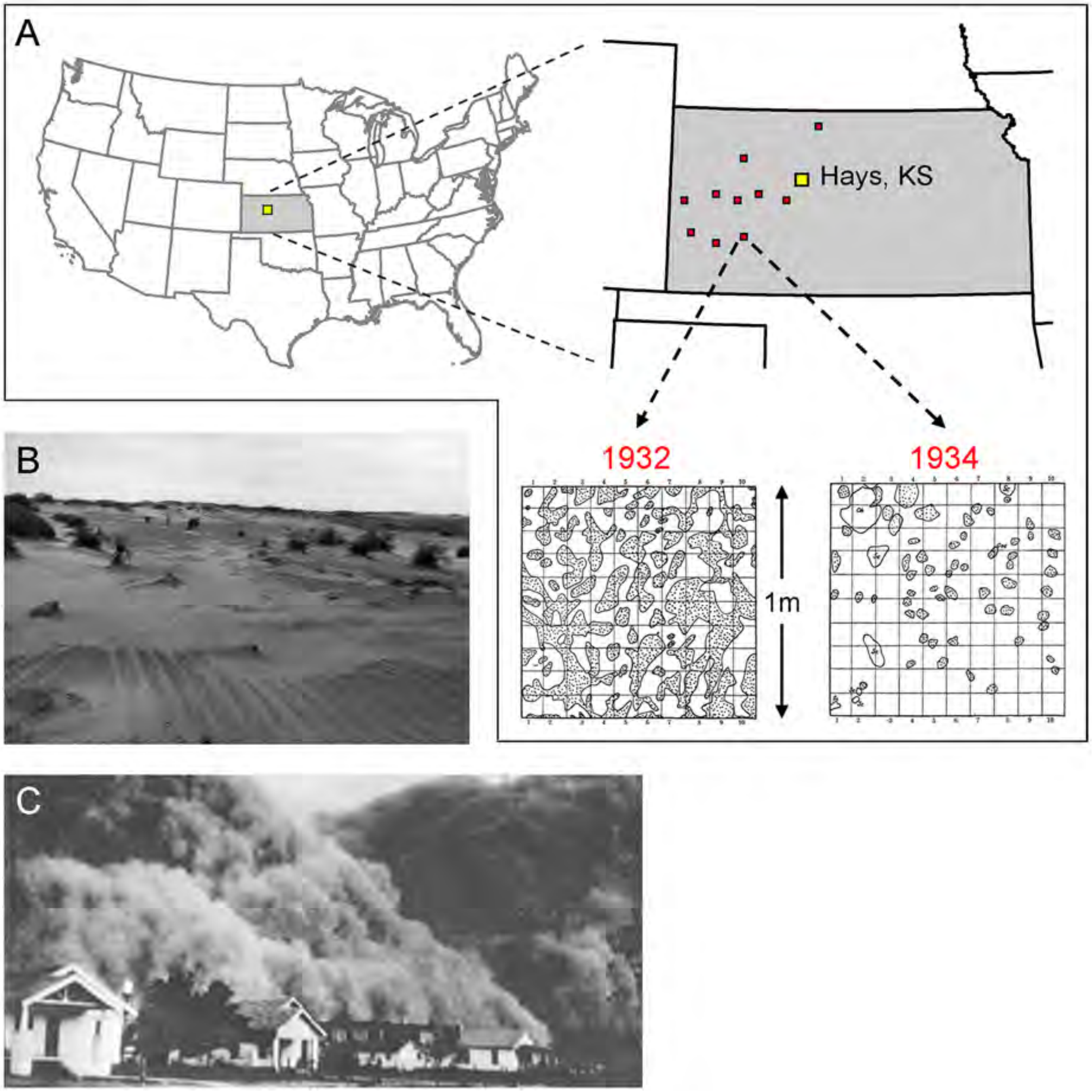

Fig. 1. The Dust Bowl of the 1930s in the U.S. exemplifies how fine-scale processes can propagate spatially to have dramatic and surprising effects at the continental scale. (A) Sampling of vegetation on small, 1-m^2 quadrats by the same team of scientists using the same methods occurred throughout the Dust Bowl region to document plant-scale mortality in grasslands. (B) High plant mortality led to landscape-scale erosion and deposition by soil. (C) These fine-scale effects propagated spatially as very large areas were connected by wind that led to large dust storms.

ecologists "take the pulse of a continent" given that most of the information on ecological responses to environmental drivers, and their interactions, is obtained from finer spatial scales? What is needed in the future to enable ecologists to improve understanding of these broad-scale events in order to be better prepared for their occurrence?

Here, we show that a modified research infrastructure is needed to address regional- to

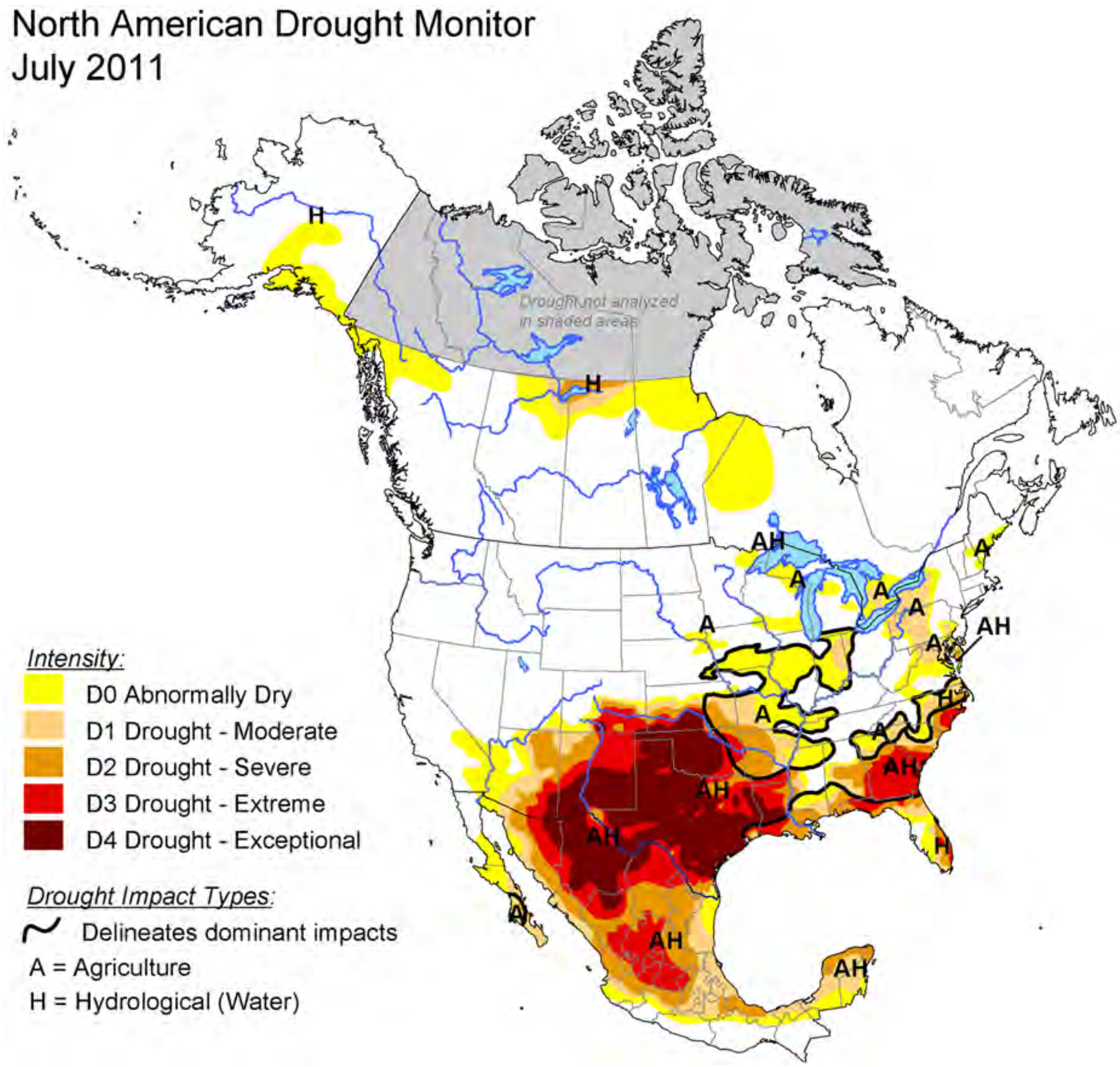

Fig. 2. The drought of 2011 affected most of the North American continent, similar to the 1930s drought. The landscape conditions and the interactions with drought that are needed for another Dust Bowl remain unknown. The figure was downloaded from National Oceanic and Atmospheric Administration National Climatic Data Center: http://www.ncdc.noaa.gov/temp-and-precip/drought/nadm/nadm-maps.php. Some original figure legends were removed to improve clarity of the figure.

continental-scale ecological questions given the pace, pattern, and scale of environmental changes occurring now and expected in the near future. First, we review the types of approaches used to address broad-scale questions. Second, we identify the research, cyber-infrastructure, and cultural challenges associated with these questions. Third, we discuss the strengths and limitations of current site-based research infrastructures and organized networks to meet these challenges. Finally, we describe a regional- to continental-scale research infrastructure that integrates existing sites and multiple networks with emerging and potentially new technologies to more effec-

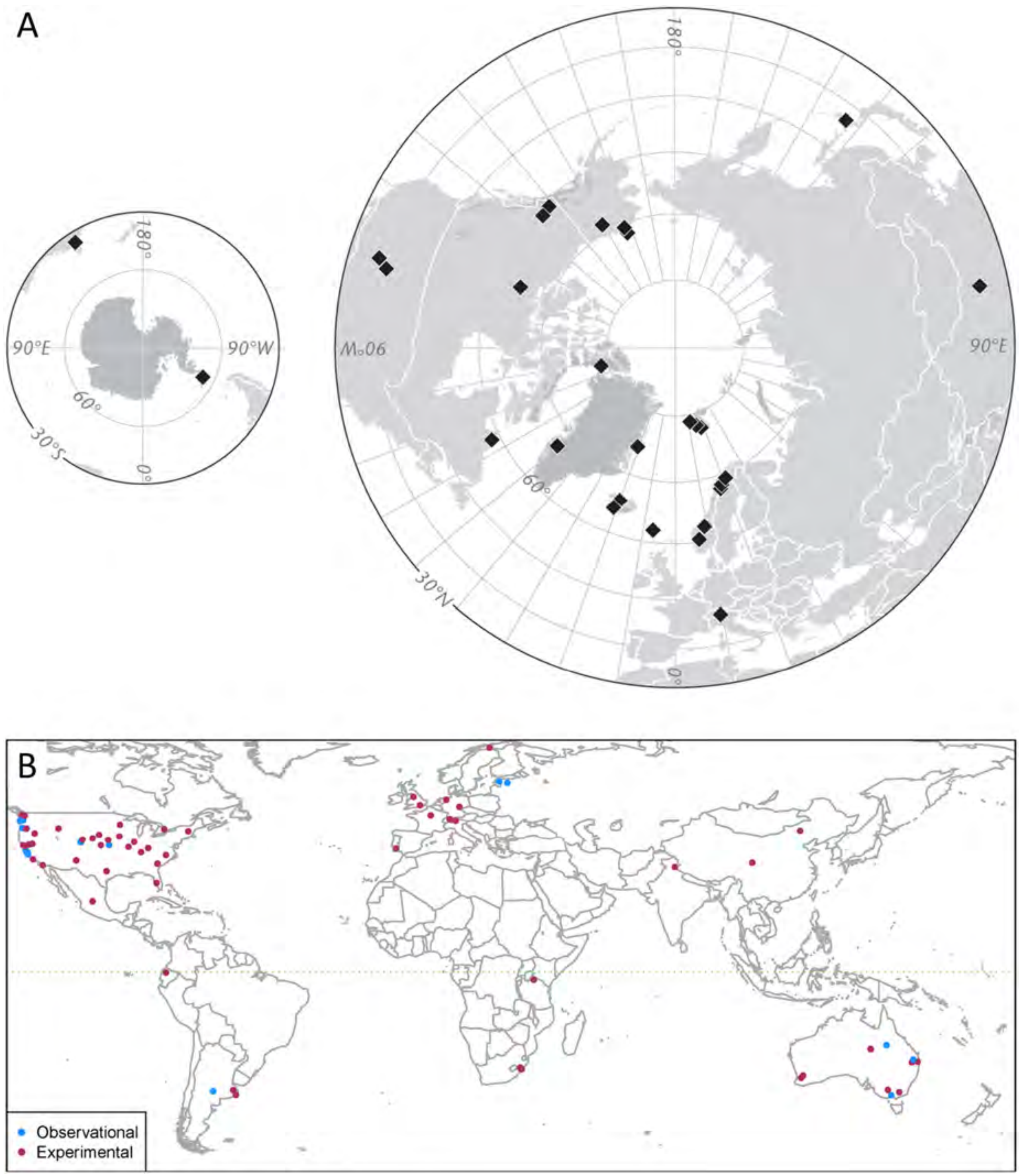

Fig. 3. Two examples of large-scale experiments where research plots within globally distributed sites are the focal units of study: (A) the International Tundra Experiment (ITEX) with circumpolar sites to address the potential effects or climate warming on tundra vegetation (www.geog.ubc.ca/itex, map reproduced with permission from Elmendorf et al. 2012), and (B) The Nutrient Network (NutNet) with sites located around the world is being used to experimentally address the effects of anthropogenic nutrient inputs and herbivores on ecosystem composition and function (www.nutnet.org, see Borer et al. 2014 for details).

tively address broad-scale questions with consequences for ecosystems and the services they provide to humans.

APPROACHES TO ADDRESSING REGIONAL- TO CONTINENTAL-SCALE QUESTIONS

Questions that require a broad-scale perspective involve understanding and predicting the properties or dynamics of one or more biological levels of organization (i.e., entities) distributed across a geographically extensive area. Spatially distributed sampling is required to capture variability in environmental drivers and the biophysical template across this large spatial extent. Approaches to addressing these continental-scale questions can be classified into one of three types (non-spatial, spatially implicit, spatially explicit; Peters et al. 2004*b*) that differ in: the amount and type of spatial information needed to address the question, and the assumptions required to extrapolate from fine-scale studies to a continent. Although these approaches can be important at finer spatial scales, and we recognize the importance of spatial variation across all levels of organization, here we focus on addressing questions relevant to understanding and predicting spatial variation in ecosystem types across a very broad spatial extent.

Non-spatial approaches have a long history in ecology as a way to compare within and among ecosystem types, and to identify relationships between response variables and environmental drivers when spatial location is not an important predictor variable. For example, mean or interannual variability in aboveground net primary production (ANPP), the response of ANPP to environmental variables, and trends in ANPP through time have been compared within and among terrestrial biomes on many continents for decades (e.g., Whittaker 1975, Le Houérou and Hoste 1977, Sala et al. 1988, Huxman et al. 2004, Guo et al. 2012, Hsu et al. 2012).

Spatially implicit approaches require similar information about ecological properties and environmental drivers as non-spatial approaches, but spatial information is also needed to reduce variance in the response variables. This type of approach is often used to understand or explain differences among ecosystem types based on spatial metrics, such as geographic location, distance, adjacency, and contingency (e.g., Ladd et al. 2013, Peters et al. 2013). A key assumption is that spatial metrics contain information about rates of transfer among ecosystem types such that these rates are not measured directly. For example, the location of the shortgrass steppe in the rainshadow of the Rocky Mountains in North America explains why rainfall, and consequently ANPP, increase eastward to the tallgrass prairie. This information about spatial location is sufficient to understand patterns in ANPP without measuring the influence of mountains on rainfall amount. Spatially implicit approaches have become increasingly popular as software and hardware technologies associated with geographic information systems have improved the acquisition, resolution, and analysis of field-based measures, imagery, and maps (e.g., Zhang et al. 2012, Yu et al. 2013).

Spatially explicit approaches require additional information beyond that needed for spatially implicit questions to include measurements of fluxes or flows that connect levels of organization or spatial units. At regional to continental scales, transport vectors of wind, water, and animals connect different ecosystems via the redistribution of soil, plant material, water, and nutrients (Peters et al. 2008). A key assumption of spatially explicit approaches is that transport of materials, energy or information provides important information that needs to be measured to minimize variance in the response variables (Peters et al. 2004*b*). Spatially explicit approaches are particularly important when connectivity between ecosystems leads to events that either propagate or dissipate through time to impact large spatial extents. Propagating events include wildfire where a single source can lead to a fire that spreads rapidly and nonlinearly to affect thousands of hectares of forest, and have regional to continental-scale effects on air and water quality (Peters et al. 2004*a*). Insect outbreaks, dust storms, and floods are additional examples of events that can propagate through time to influence ecosystems at broad scales (Lehner et al. 2006, Crowl et al. 2008, Marshall et al. 2008, Field et al. 2010). Dissipating events include tsunamis and volcanic eruptions that begin with high intensity across small or large spatial extents, and although the intensity decreases spatially, the impact of the event can continue to spread to impact ecosystems globally (Self 2006, Chatenoux and Peduzzi 2007). Although effects of dissipating events on ecological systems are often under-estimated or ignored, there is clear evidence of their importance on ecosystems globally. For example, the massive eruption of Mount Pinatubo in the Philippines in 1991 had global impacts by reducing temperatures and increasing sulfur dioxide aerosols (McCormick et al. 1995). Oceanic earthquakes that generate tsunamis can influence coastal ecosystems locally and at long distances from the initial impact with the potential to be transoceanic (Okal and Synolakis 2008) and with long-lasting ecological impacts (Barbier 2006).

RESEARCH, CYBER-INFRASTRUCTURE, AND CULTURAL CHALLENGES AT REGIONAL TO CONTINENTAL SCALES

Similar to studies at smaller spatial extents, regional- to continental-scale studies need to include: (1) monitoring or observational data to document status, establish a baseline understanding, and distinguish short-term variability from long-term trends, (2) experimental data for mechanistic understanding, and (3) analytical and simulation tools for prediction. Many finer-scale studies include the importance of spatial and temporal variation (e.g., legacies, lags, thresholds, hysteresis) in global change drivers and ecological responses that lead to linear or nonlinear dynamics within and among spatial scales (e.g., Bestelmeyer et al. 2011, Sala et al. 2012). However, there are additional challenges associated with research, cyber-infrastructure, and the scientific culture that are needed to address broad-scale questions regardless of the approach used (non-spatial, spatially implicit, spatially explicit).

Research challenges at regional to continental scales

Many ecological studies combine fine-scale spatial variation in the biotic and physical environments with temporal variation in broad-scale drivers to explain dynamics within and among ecosystems. However, regional- to continental-scale questions also require an understanding of spatial patterns in broad-scale drivers (e.g., temperature, precipitation, atmospheric deposition, human activities), and how their variation interacts with biotic patterns and processes at finer scales to influence the dynamics of multiple ecosystems (Peters et al. 2008, Sierra et al. 2009). A key challenge is obtaining both spatial coverage of data across a large and diverse geographic extent, and detailed, mechanistic understanding of the drivers of ecosystem dynamics. This understanding depends on knowing how the dynamics are related to baseline conditions (i.e., long-term mean and trend in the data), and to ancillary information that may be available from site characterizations (e.g., soil and digital elevation maps) or from previous studies.

Interactions across scales often require a spatially explicit approach with measurements of the redistribution of materials among spatial units or levels of biological organization that can be challenging to obtain with low uncertainty. For example, broad-scale variation in climate or disturbance events combined with variation in physical characteristics at the landscape scale can alter biogeochemical cycling and fluxes among levels of biological organization at the local scale that can be difficult or costly to measure with high accuracy (e.g., Rhoades et al. 2013). Fine-scale biophysical factors interacting with broad-scale climatic drivers can propagate spatially across spatial units to generate landscape- to regional-scale heterogeneity (e.g., Miller et al. 2012). This heterogeneity can feed back to generate nonlinear changes in the broad-scale drivers themselves, as exemplified by dust storms and wildfires, that are challenging to measure (Schubert et al. 2004, Cook et al. 2009). These catastrophic events are often unpredictable and can increase rapidly from a small, isolated impact to broad scale events that require a multi-scale, rapid response strategy.

Although many research sites are located in natural ecosystems where one ecosystem type is commonly the focus of study, human activities that lead to other types of ecosystems typically become an increasingly larger proportion of the area as the spatial extent of interest increases. These human-dominated ecosystem types create unique challenges to all three approaches applied at broad scales. Humans have a large and diverse suite of activities that influence landscape patterns, including timing (past and present) of land use (e.g., agricultural, forest, range, pasture, urban, suburban) and type of land management based on ownership (e.g., private, state or federal) that influence land cover as well as use (Grimm et al. 2005). A mosaic of natural and human-dominated ecosystem types may necessitate different methods, frequencies, and intensities of sampling, and potentially different technologies to capture important dynamics. In addition, the location of natural ecosystems (i.e., downwind, upslope, distance) relative to human-dominated ecosystems can influence the impact of one ecosystem type on another (Grimm et al. 2008). These location-related effects need to be measured or estimated for spatial approaches or assumed negligible for a non-spatial approach. Similarly, interactions among natural ecosystems of different types, such as ecotones between forests and grasslands or between terrestrial and aquatic ecosystems, increase in frequency and importance as spatial extent increases, that also lead to sampling challenges (Williamson et al. 2008, Myster 2012).

Cyber-infrastructure challenges at regional to continental scales

As the number of sites, ecosystem types, and investigators increase, so does the complexity of the cyber-infrastructure needed to collect, handle, transform, analyze, and archive the data for all three types of spatial approaches (Jones et al. 2006, Reichman et al. 2011). Here we refer to 'data' as structured data (e.g., quantitative measures), unstructured information (qualitative attributes), and the associated informatics (i.e., metadata, data formats, controlled vocabularies, and other descriptors of the data and variables in a dataset). Cyber-infrastructure (CI) broadly refers to the hardware and data acquisition technology, informatics, and supporting human expertise required to support scientific discoveries.

Hardware and data acquisition technology.—At broad spatial scales, a diversity of methods, sampling protocols, and data acquisition technologies makes post hoc comparisons of multiple ecosystems using existing data challenging (Yao et al. 2013). Most questions at this scale have to be addressed by multiple sources, types, and qualities of data, often at different, but complementary time and space scales (Schimel et al. 2011). Data collected from studies with different objectives or at different points in time are often challenging to compare, even within the same ecosystem type, because of changes in sampling intensity or frequency (e.g., Lauenroth and Sala 1992). These challenges are even more likely when comparing ecosystem types where the same sampling method or analyses cannot be applied to all sites (e.g., Knapp and Smith 2001). For example, comparisons of deserts, grasslands, and forests necessitate different methods to estimate ANPP by different life forms (e.g., succulents, grasses, trees) (Fahey and Knapp 2007). Comparing ecosystems often requires aggregations or transformations to a common metric, such as g/m^2 or kg/ha (Peters et al. 2013), that lead to additional sources of error (Taylor and Loescher 2013).

Alternatively, regional- to continental-scale comparisons of ecosystem types can be "by design" where system attributes are measured with similar methods under similar environmental and biotic conditions (e.g., timing, phenological stage) to minimize bias (Kao et al. 2012). However, data collected using standardized methods across sites are challenging to implement given the high degree of coordination and teamwork required among geographically distributed individuals and groups (e.g., Robertson et al. 1999, Parton et al. 2007).

The suite of data needed to address broad-scale questions can include data collected or analyzed using a combination of old and new technologies that lead to additional challenges. Data from older technologies continue to be used either because of budget and personnel constraints on purchasing, deploying, and monitoring new technology or a history of use that includes well-calibrated legacy data. Most individual investigator-led, multi-site studies use technology and sampling methods that require fewer resources per location than desired. These methods can lead to a mismatch of sampling scales and/or signal-to-noise ratios compared to the scales of ecological phenomena (Fraser et al. 2013). For example, distributed grids of wireless soil temperature measurements with low accuracy and precision can be appropriate to estimate the variance structure in soil temperature, but are insufficient to extrapolate fine-scale absolute measurements to larger scales (Pottie and Kaiser

2000). Technological advances in ground and airborne sensors collect data at increasingly finer and broader temporal and spatial scales to allow this extrapolation (Porter et al. 2009, Hasselquist et al. 2010, Kampe et al. 2010). However, comparing data collected using older technology with data from newer sensors can lead to otherwise larger uncertainties and invalid conclusions, thus making a type II error. In some cases, the new technologies do not have a historic counterpart (e.g., ground-penetrating radar, stable isotope fluxes) or the new data may be collected at sufficiently different spatial or temporal resolutions that make comparisons less robust. These challenges are particularly important when comparing spatially distributed ecosystems across a large spatial extent where a wide range of technologies are used to measure similar ecosystem attributes.

Informatics.—Even when the same sampling protocols and technology are used across all sites or sampling locations, differences among investigators and sites in data accessibility, nomenclature (semantics and controlled vocabularies, e.g., Reichman et al. 2011, Deck et al. 2013), and archival processes can lead to challenges (Laney et al. 2013, Taylor and Loescher 2013). Data availability on-line is typically poor unless there is a strong centralized information system or mandate by a funding agency (Baker et al. 2000, Reichman et al. 2011). Recent open data policies by the U.S. and other governments ensures that data and associated metadata are posted on-line in machine readable formats (e.g., Global Open Data for Agriculture and Nutrition Initiative [www.godan.info]), yet data accessibility and use are still limited unless software tools and derived data products are also readily available (Peters 2010, Michener and Jones 2012). In addition, long-term data storage of investigator-based research is typically at the host university or institution without archival-level sustainability, although efforts are increasing to provide long-term archival services and to link open access publications with openly available data (e.g., Vision 2010, Whitlock 2011).

Human expertise.—At regional to continental scales, there are similar challenges in expertise required to verify, interpret, and manage large quantities of diverse data for all three types of approaches. The highest degree of quality control occurs when an individual investigator collects the data or supervises the collection, routinely calibrates and verifies data accuracy, precision, and completeness, performs quality checks, and provides online availability of the data and metadata (Taylor and Loescher 2013). This individual-investigator model is often replaced by an information manager when many investigators work at the same site or multiple sites are involved. An information manager working with investigators to routinely examine the data can reduce error propagation through time. However, this relationship may not be consistent among geographically distributed sites where each site has an information manager with a different level of expertise, funding level, and availability of software and hardware (Baker et al. 2000).

Alternatively, standardized data collection and management at many spatially distributed sites by a team composed of members who lack a detailed understanding of the sites and ecosystems can also lead to challenges associated with information management and use of data. For example, an analysis of long-term rainfall and ANPP data that distinguishes responses during an extended drought from a multi-year wet period leads to different conclusions than an analysis where all years are assumed to be independent (Peters et al. 2012*b*). Managers and users of the data who are unfamiliar with the site and its ecosystem properties, and do not account for differences in climatic periods, will likely have incomplete metadata, inaccurate analyses or incorrect interpretations.

Cultural challenges at regional to continental scales

Traditionally, data sharing and collaboration (i.e., open science) have not been part of the culture of ecologists (Reichman et al. 2011, Hampton et al. 2013). Both the bottom-top (i.e., scale up from measured, sensed or simulated plots to understand and predict dynamics at the continental scale [e.g., Keller et al. 2008, Schwartz et al. 2012]) and top-down (i.e., use imagery from airborne or satellite platforms to examine patterns and dynamics across large spatial extents, and then attempt to scale down to underlying mechanisms within plots or research sites [e.g., Ponce-Campos et al. 2013]) methods are typically individual investigator-driven research. These methods would benefit from extensive data sharing and collaboration, although the culture of ecology would need to change to promote and reward these interactions (Wolkovich et al. 2012, Hampton et al. 2013). There are additional challenges associated with geopolitical differences among countries that can constrain continental-scale studies (Vargas et al. 2012).

Opportunities are increasingly available for individual investigators to participate in open science by making their data accessible as part of larger efforts, including intergovernmental projects (e.g., International Council for Science [http://www.icsu.org/future-earth]; CoopEUS [www.coopeus.eu]; Killeen et al. 2012), federated networks (e.g., Ecoinforma [President's Council of Advisors on Science and Technology 2011]), consortia, and non-profit organizations (e.g., DataONE [www.dataone.org], Earthcube [http://earthcube.ning.com]). Data linked to publications can be published as separate entities by scientific societies, journals, or non-profit organizations (e.g., Ecological Archives [www.esapubs.org/archive/], Dryad [www.datadryad.org/]). Open-access journals allow a broad readership to view data, videos, and dynamic graphics within the context of an online journal article (e.g., Ecosphere [www.esapubs.org], PLOS ONE [www.plosone.org]). The interest in open access to data and metadata has led federal governments in a number of countries to develop policies about data sharing for government-funded projects (e.g., President's Council of Advisors on Science and Technology 2011, Holdren 2013*a*, AusGOAL [www.ausgoal.gov.au]) and to participate in multi-national efforts, such as GODAN (www.godan.info).

Beyond data sharing, there are other cultural challenges in sharing, preserving, and automating the algorithms and workflows used in assuring, analyzing, and visualizing data (Michener and Jones 2012). These activities support reproducible research (Hollister and Walker 2007), and are critical elements in the ability of ecologists to use large, diverse datasets. A cultural shift with clear rewards for collaboration throughout the data life cycle will be needed before investigator-based analyses can foster community-accessible efforts (Wolkovich et al. 2012).

STRENGTHS AND LIMITATIONS OF CURRENT RESEARCH INFRASTRUCTURES

Regional to continental-scale questions have typically been addressed using data from spatially distributed research sites selected to represent ecosystem types (e.g., Knapp and Smith 2001, Huxman et al. 2004, Herrick et al. 2010). These multi-site comparisons are limited to specific questions and sites where comparable data are readily available. Research at an individual site can contribute to broad-scale questions when combined with data from other sites, but the site by itself cannot address challenges associated with these questions (Fig. 4). To address some of the challenges described above, this site-based research infrastructure has been complemented with organized networks of sites with similar goals, methods, information management, a common funding source, and centralized management (Baker et al. 2000). In a network, data are shared, synthesized, and integrated across sites such that diverse ecosystem types can be compared for a number of questions and variables by the research community through time (e.g., Gottfried et al. 2012, Peters et al. 2013).

Here we compare the strengths and limitations of three types of organized networks found globally in addressing broad-scale questions. These research infrastructures differ in their underlying philosophy, structure, and overall goals that lead to differences in the degree to which they address the research, CI, and cultural challenges described above. To facilitate general comparisons, we classify individual networks into one type (Tables 1–3), although we recognize that networks within a type have diverse characteristics, and that a site may be a member of more than one network. We also recognize that ecological research occurs at many sites that are not part of any organized network. Integrating data from these sites into a regional- to continental-scale research infrastructure is described in the next section.

Long Term Research Networks (LTRN) consist of sites where the research goal is to develop a mechanistic understanding of the ecology of each site that represents an ecosystem type (Fig. 4). Observations and experiments conducted by a number of researchers over a long period of time

Site-based scientific creativity

Challenges to continental-scale research	Site	NETWORKS			Synergistic or in combination
		LTRN	CDEO	EON	
Research					
1. Spatial coverage	very weak	weak/ moderate	strong/ very strong	moderate	Very Strong
2. Mechanistic understanding	strong	very strong	weak/ moderate	very weak	Very Strong
3. Knowledge of baseline conditions	weak/ strong	very strong	weak/ moderate	very weak	Very Strong
4. On site-characterization	weak/ strong	very strong	weak/ moderate	very weak	Very strong
5. Human dominated/ managed ecosystems	very weak	weak/ moderate	weak	weak	Moderate
6. Linkages among ecosystem types	very weak	very weak	very weak	weak	Weak
Cyberinfrastructure					
1. Hardware and data acquisition	weak	moderate	weak/ moderate	very strong	Very Strong
2. Informatics	weak	very weak/ moderate	weak/ moderate	very strong	Very strong
3. On-site expertise	strong	very strong	weak	very weak	Very strong
Culture					
1. Data sharing	weak	weak to moderate	moderate	very strong	Very strong
2. Collaboration	weak	weak to moderate	moderate	very strong	Very strong

Level of top down management

Fig. 4. Characteristics of three types of networks (LTRN, CDEO, EON) and individual research sites in terms of the research, cyber-infrastructure, and cultural challenges associated with conducting continental-scale ecological research. Each network is described from very weak to very strong, and the synergistic ranking is based on the highest rank of the elements in that row. As a combined score, an individual site has the highest site-based creativity (green arrow) and EONs have the highest degree of top-down management (pink arrow).

leads to knowledge of baseline conditions and on-site characterizations (e.g., climate, soils, biota) used to develop mechanistic understanding of ecosystems (e.g., Havstad et al. 2006). These site-based studies examine the importance of within-site spatial heterogeneity across a range of spatial and temporal scales. Similar measurements of common variables and standards for information management allow data to be compared to address new, initially unintended

Table 1. Long Term Research Networks (LTRNs). This is not an exhaustive list, but is presented to demonstrate the global distribution, diversity, and duration of LTRNs.

Name	Description	Location	Start date	Website
ALTER-Net (A Long-Term Biodiversity, Ecosystem and Awareness Research Network)	Biodiversity	Europe	2004	http://www.alter-net.info/
Ameri-Flux	Micro-meteorology	North America	1996	http://public.ornl.gov/ameriflux/
Fluxnet	Micro-meteorology	Global	1999	http://fluxnet.ornl.gov/
GLORIA (Global Observation Research Initiative in Alpine Environments)	Alpine	Global	1999	http://www.gloria.ac.at/
ILTER (International Long Term Ecological Research)	Ecology	Global	1993	http://www.ilternet.edu/
LTAR (Long Term Agroecosystem Research Network)	Agricultural systems	United States	1912	http://www.ars.usda.gov/research/programs/
LTER (Long Term Ecological Research Network)	Ecology	United States	1980	http://www.lternet.edu/
NADP (National Atmospheric Deposition Program)	Atmospheric chemistry deposition	North America	1978	http://nadp.sw.uiuc.edu/
Paleoclimatology Pollen	Pollen	Global	2008	http://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/pollen /
SAEON (South African Ecological Observatory Network)	Terrestrial ecosystems	South Africa	2002	http://www.saeon.ac.za/
TERN (Terrestrial Ecosystem Research Network)	Terrestrial ecosystems	Australia	2009	http://tern.org.au/
USFS (U.S. Forest Service)	Forests	United States	1908	http://www.fs.fed.us/

multi-site questions (e.g., Moran et al. 2008, Bestelmeyer et al. 2011). Combining accessible long-term data that spans multiple levels of biological organization and spatial scales with site-based expertise provides a strong research infrastructure for additional place-based research, and for enhancing continental-scale research that builds on this deep understanding.

These networks are typically bottom-up approaches and their collective understandings are

Table 2. Coordinated Distributed Experiments and Observations Networks (CDEOs). This is not an exhaustive list, but is presented to demonstrate the global distribution, diversity, and duration of CDEOs.

Name	Description	Location	Start date	Website
AnaEE (Analysis and Experimentation on Ecosystems)	Ecosystems	Europe	2012	http://www.anaee.com/
DRAGON (Delta Research and Global Observation Network)	Delta costal systems	Global	2007	http://deltas.usgs.gov/
GLEON (Global Lake Ecological Observatory Network)	Lake ecology	Global	2005	http://www.gleon.org/
ISCN (International Soil Carbon Network)	Soil carbon	Global	2010	http://www.fluxdata.org/nscn/
ITEX (International Tundra Experiment)	Ecosystem warming	Arctic tundra	1992	http://www.geog.ubc.ca/itex/
LIDET (Long-term Inter-site Decomposition Experiment Team)	Decomposition	United States	1990	http://andrewsforest.oregonstate.edu/research/intersite/lidet.htm
NutNet (Nutrient Network)	Nutrients	Global	2006	http://www.nutnet.umn.edu/
PalEON (Palo-Ecological Observatory Network)	Forests, fire and climate	NE US	2011	http://www3.nd.edu/~paleolab/paleonproject/
STREON (Stream Experimental and Observatory Network)	Streams	United States	2014	http://www.neoninc.org/

Table 3. Ecological Observatory Networks (EONs). This is not an exhaustive list, but is presented to demonstrate the global distribution, diversity, and duration of EONs.

Name	Description	Location	Start date	Website
DOE ARM (U.S. Department of Energy Atmospheric Radiation Measurement)	Atmospheric radiation	Global	1993	http://www.arm.gov/
EuroSITES (European Ocean Observatory Network)	Oceans	Europe	2008	http://www.eurosites.info/
GEO BON (Group on Earth Observations Biodiversity Observation Network)	Biodiversity	Global	2008	http://www.earthobservations.org/geobon
GEOSS (Global Earth Observation System of Systems)	Environmental	Global	2007	http://www.earthobservations.org/geoss.shtml
ICOS (Integrated Carbon Observation System)	Terrestrial and oceanic systems; greenhouse gases	Europe	2014	http://www.icos-infrastructure.eu/
NASA (National Aeronautics and Space Administration)	Photos, imagery, radar	Global	1930	http://www.nasa.gov/missions/
NEON (National Ecological Observatory Network)	Terrestrial and freshwater ecosystems	United States	2013	http://www.neoninc.org/
NOAA USCRN (National Oceanic and Atmospheric Administration US Climate Reference Network)	Climate Reference Network	United States	1997	http://www.ncdc.noaa.gov/crn/
OOI (Ocean Observatories Initiative)	Oceans	Western hemisphere	2014	http://oceanobservatories.org/
TEAM (Tropical Ecology Assessment & Monitoring Network)	Biodiversity of tropical forests	Global	2009	http://www.teamnetwork.org/

often the product of individual research projects that are rich with scientific creativity and expertise. While each network takes on their own development path with individual nuances and responses to their research needs, some organizational patterns emerge. Within each LTRN, selection of individual sites and associated research foci are often the product and self-selection of a collaborative group of on-site scientists. The nature of this style of development has high comfort level with scientists. The scientific complexity is often enhanced by adding scientists with complementary disciplines or new questions that lead to additional studies and research foci, and is ultimately constrained only by funding opportunities.

However, LTRNs consist of a relatively small number of research sites with small-to-modest investments in hardware and data acquisition technology. Research is dominated by individual investigator-led projects with specific goals and non-standardized methods that lead to unquantifiable differences in the measurement signal-to-noise ratio among sites that limits the utility and rigor of quantitative comparisons (Madin et al. 2008). At the continental scale, spatial gaps in coverage occur because the number of sites is limited by funding opportunities, and sites are selected based on investigator interest or funding agency priorities rather than a scientifically defensible design. Human-dominated ecosystems are infrequently included in the study design of a network (e.g., only 2 of 25 sites in the LTER network are urban; Table 1), and ecosystems managed for food and fiber are primarily studied in networks with federal mandates (e.g., USFS, LTAR; Table 1). Linkages among ecosystem types are rarely studied. Data sharing depends on the organizational structure of each network, and primarily consists of the online posting of source data and metadata. Collaboration occurs most frequently among scientists working at the same site or within the same ecosystem type. These LTRNs have typically not demonstrated the culture required to jointly develop questions, hypotheses, and resulting scientific approaches for regional- to continental-scale research.

Coordinated Distributed Experiments and Observations (CDEO) consist of sites linked by similar sampling methods and experimental designs where the goal is to understand broad-scale patterns and dynamics of multiple ecosystems by maximizing participation of sites through the use of small investments in research infrastructure (i.e., equipment, sampling effort). This is a very diverse collection of sites and networks that includes coordinated experiments (described in Fraser et al. 2013) and long-term observations (e.g., Parton et al. 2007) (Table 2). In many cases, these networks are formed by adding measurements and studies to existing research sites. Because the investment can be small for each sample location, the spatial coverage by the collection of sites in the network can be quite extensive (Fig. 4). Data sharing and collaboration occur most frequently within a CDEO using a centralized information management system and a common internet home page.

At broad scales, standardized methods for selected variables allow for robust comparisons among sites (e.g., Adler et al. 2011, Fraser et al. 2013; H. W. Loescher et al., *unpublished manuscript*). However, there is also large unexplained variance because representative sample locations within a site are chosen based on individual preference, rather than by a statistically defensible design (e.g., Clark and Clark 2000, Palmer et al. 2000). The length of record varies for each site, from a single year to decades, and measurements may not be synchronized among sites (Fraser et al. 2013). Because participation is by individual investigators with limited resources, ancillary measurements for site characterization, additional on-site expertise, and results from experiments are not available to provide mechanistic explanations for broad-scale patterns (Grace et al. 2012). Human-dominated systems, managed systems, and linkages among ecosystem types are rarely studied. Although most CDEOs have data collection and accessibility standards, the full data life cycle is rarely standardized and the long-term sustainability of the network-wide data is unknown. These networks have typically lacked the spatial breadth and temporal duration required to address regional- to continental-scale research.

Ecological Observatory Networks (EON) consist of sites that are selected geographically with the goal of addressing broad-scale questions using standardized measurements and large, often costly, community-designed and -shared infrastructure (Table 3) (e.g., Keller et al. 2008, Kao et al. 2012; http://www.saeon.ac.za/, http://www.tern.org.au/). For these networks, the science community self-organizes to identify large-scale Grand Challenge science questions that can only be addressed by costly infrastructure that is then funded and shared as a community resource (e.g., National Research Council 2001, National Research Council 2003). EONs are typically designed to provide consistent, multi-scaled data products that are traceable to known and accepted first-principles, nationally or internally recognized standards, or best community practices. Sampling and measurements are centrally organized and coordinated through a top-down management structure that leads to strong data sharing and the potential for multiple collaborations using open access data and derived data products (Fig. 4).

Because EONs are a relatively new concept in ecology, the data record is currently short for response variables, and the community is adjusting culturally to this new paradigm for broad-scale research. There are many analogs to EONs in other scientific disciplines that provide operational examples as well as illustrate the potential for novel research findings (Kerr 2013). Teams of technicians managing the data flow can minimize sampling error, but also limit the opportunity for the ecological community to provide expert input on novel data products or to assist in error checking and data interpretation. Similar to CDEOs, mechanistic understanding of within-site heterogeneity is not typically part of the sampling design, and spatial gaps in coverage occur at regional to continental scales as a result of tradeoffs in the number of spatially distributed sites versus costly infrastructure provided at each site. In some network designs, linkages among ecosystem types are being investigated with a small set of variables, and comparisons of land use and management are possible (e.g., NEON). Although broad-scale comparisons within an EON are enhanced through the use of standardized sampling methods and complex technologies, this approach can produce data that may not have the same signal-to-noise ratio as site-based approaches; thus making comparisons less robust with EON data alone, in particular with legacy data collected using historical technology. These networks have lacked integration into the ecological science infrastructure and acceptance by the research community that is required to address broad-scale research.

AN INTEGRATED REGIONAL- TO CONTINENTAL-SCALE RESEARCH INFRASTRUCTURE

Although all three research infrastructures contribute to ecological understanding, none of them alone can address all of the research needed nor can they address all of the spatial, CI, human expertise, and cultural challenges presented here. Rather, a synergistic approach is required to create an integrated 'über network'. As part of this network, a research infrastructure is needed that can integrate data, information, and expertise from individual sites and multiple networks to more effectively "take the pulse of a continent" and to improve understanding of these broad-scale events in order to be better prepared for their occurrence. We envision that this research infrastructure would allow users to take advantage of current capabilities provided by sites and networks (data, hardware, software tools, expertise, technician time), and be sufficiently flexible and scalable to incorporate new technologies and capacities as they emerge. Below we describe the major components of this research infrastructure. Many of these components currently exist as individual pieces, and there is a clear need for a lead organization or agency to develop the integration among them.

We envision a future CI and ecological culture where data and associated metadata from many diverse sources as well as the programming scripts used to create derived data products are easily accessible through a web portal where information is available in a uniform way. A search engine API (application programming interfaces) would permit users to search content from different domains, including data and metadata from individual investigators, sites, networks, federated databases, and countries. The portal would also offer other services such as formatting, access, and analysis using statistical packages and simulation models. Portals, such as mashups, are commonly used by internet companies to allow users to produce results that were not necessarily the original reason for producing the raw source data. The next generation of ecological portals needs to include characteristics of mashups. Current ecological portals provide access to source data and use of personal toolkits for analysis (e.g., DataONE; www.dataone.org). However, new portals are needed that: (1) provide open access to the derived data products and programming scripts that created them, and (2) learn from previous uses of the data, similar to the way that algorithms such as PageRank from Google and others work (D. P. C. Peters and K. M. Havstad, *unpublished manuscript*). Other disciplines, such as the medical sciences, have taken advantage of these algorithms to provide rapid, scalable, robust analyses of large volumes of data (Iván and Grolmusz 2011). A novel machine learning approach would allow ecologists to access the large streams of diverse data becoming available from new sensing technologies, commonly referred to as "big data", as well as "little" data collected by individuals, and legacy data from historic applications (D. P. C. Peters and K. M. Havstad, *unpublished manuscript*).

As part of this new portal, a user would be able to easily and seamlessly identify and select sites and datasets, regardless of network affiliation, funding agency, or political affinity, to cover the spatial variability and extent needed for a regional-to continental-scale question (Fig. 4). For example in the US, spatial coverage would be improved by integrating data from sites in two LTRNs (LTAR, LTER, rf. Table 1), one EON (NEON, rf. Table 3), and one CDEO (NutNet, rf. Table 2) (Fig. 5A). Including individual sites funded by state agencies helps improve spatial coverage in the American Southwest (Fig. 5B), yet all but one of these sites (the urban CAP LTER) are located in natural ecosystems. To account for the mosaic of land use found across the continent, sites in additional CDEOS with a different history of land use can be included or alternative approaches may be needed for current patterns of land use where large areas are managed by private land owners (Fig. 6). Linkages among ecosystem types, one of the weakest parts of current infrastructures, can be studied, at least in some areas, by comparing data from sites in different networks that are located along flow channels, such as rivers to a bay (Fig. 7). Developing international collaborations and partnerships will be critical to expand-

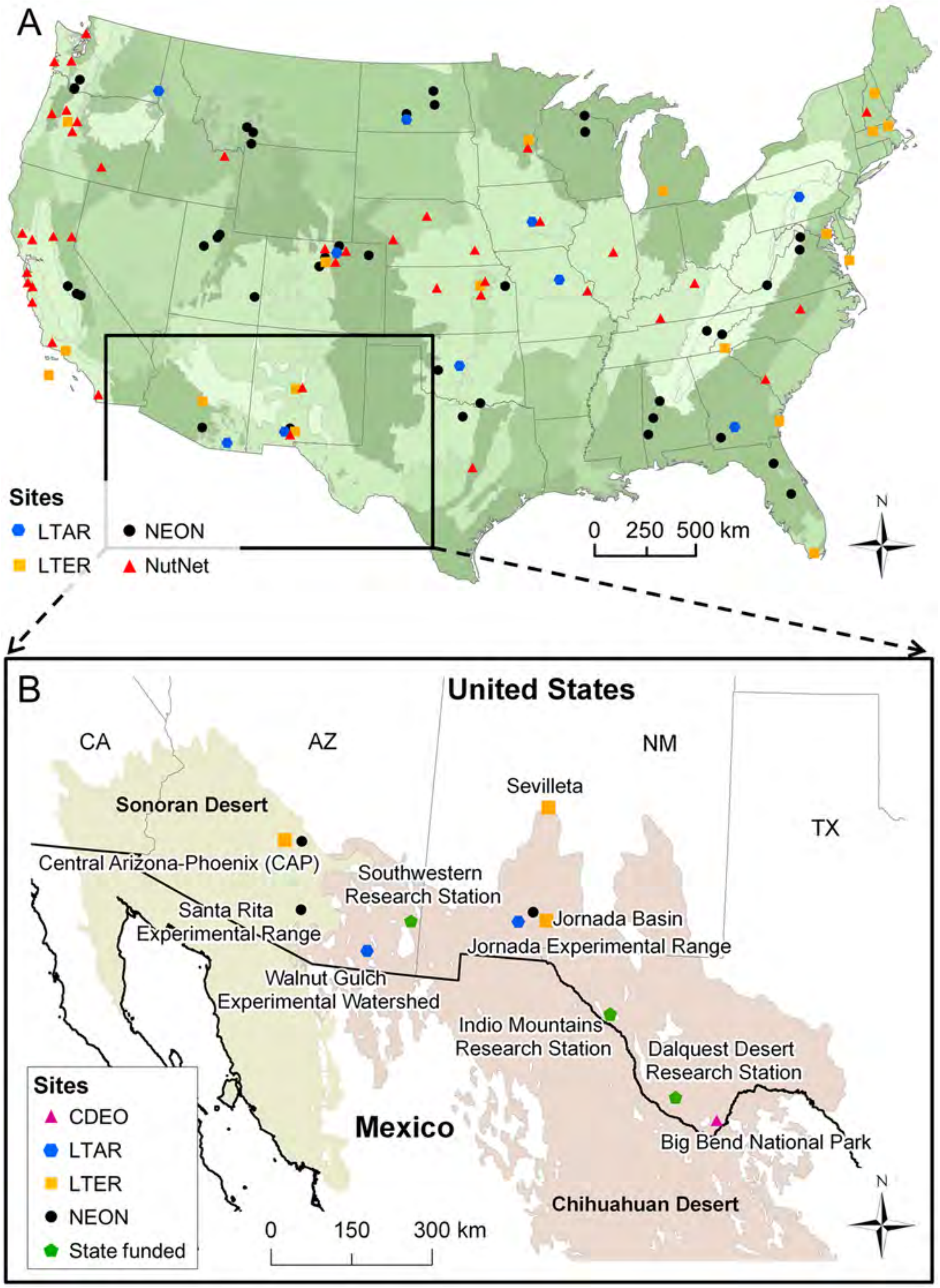

Fig. 5. To increase spatial coverage of a continent, it will be necessary to: (A) integrate similar data from multiple types of networks with (B) data from individual sites operated by state agencies (green dots).

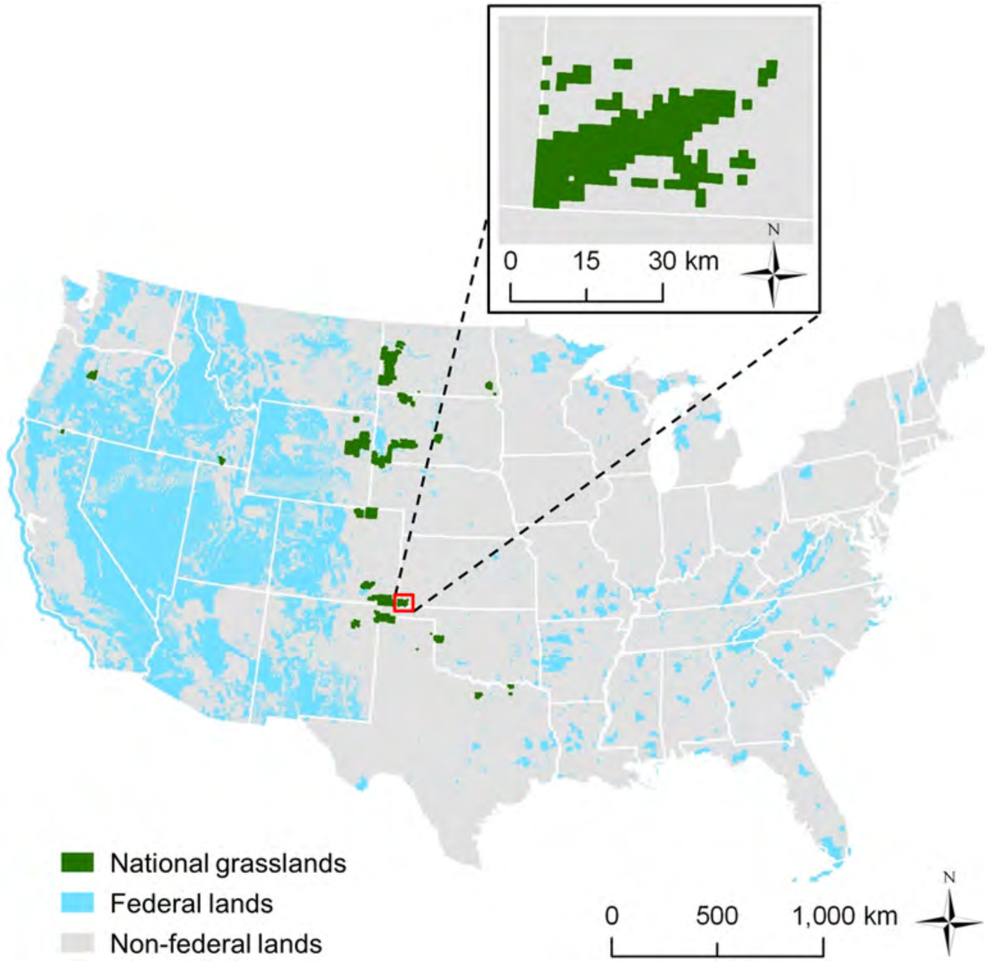

Fig. 6. Spatial coverage of a continent can be increased by integrating data from sites with known patterns in ownership, either federal (blue) or non-federal (grey). Historic land use patterns can occur (inset): USFS National grasslands formed after the Dust Bowl consist of native grassland and agricultural fields abandoned in the 1930s (green) interspersed with private land (gray).

ing to entire continents.

For many areas of the continent (and the globe), spatial gaps in coverage will remain, in particular when geopolitical boundaries are crossed. New sites and new data sets can be added if new funding is available, although the density of sites possible will likely be lower than that required to represent spatial and temporal heterogeneity across very large spatial extents. Scaling techniques will be needed to fill spatial and temporal gaps, and theory can be used to identify and prioritize critical measurements needed for broad-scale questions (Peters et al. 2012*a*).

After sites and datasets are selected, then approaches will be needed to allow synthesis of potentially different types of data. A strength of combining data from sites within all three network types with individual research sites is the diversity of data available. For example, mechanistic understanding developed at an LTRN site may be transferable to other sites within the same ecosystem type. Technological advances in hardware, software, and sampling methodologies made at EONs can be transferred with some modifications to limit cost (e.g., sampling frequency, intensity) with known errors to other sites. Theoretical patterns and general relationships developed at CDEOs can be used to

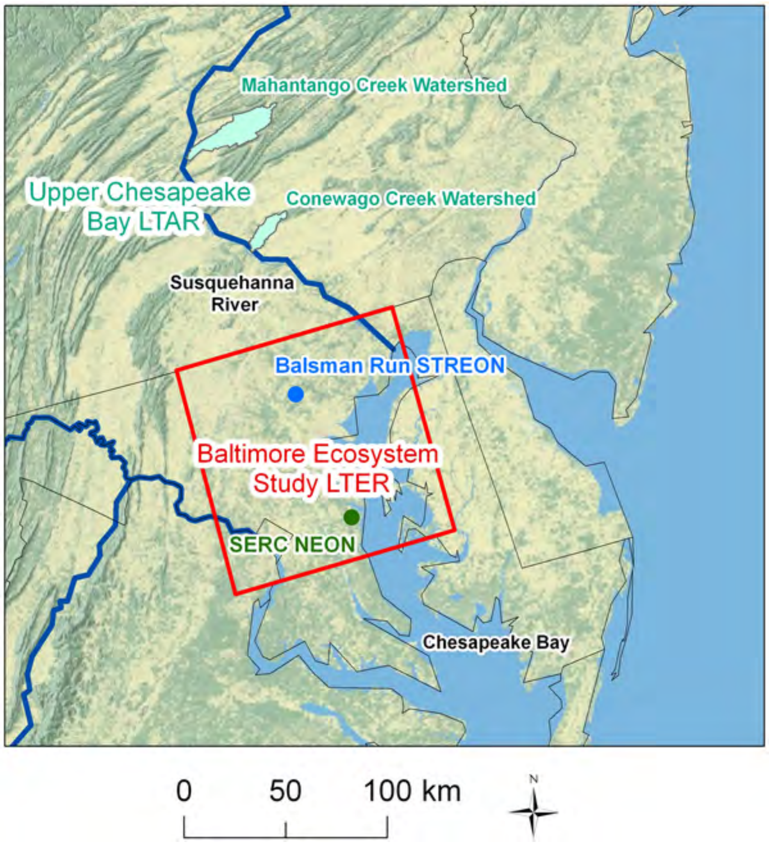

Fig. 7. Data from sites in different networks that are located in the same geographic region can be used to examine linkages among ecosystem types. For example, the Upper Chesapeake Bay LTAR site (two of the four experimental watersheds shown in light blue) is located along the Susquehanna River that flows into the Chesapeake Bay being studied by the Baltimore Ecosystem Study LTER and NEON.

provide boundaries on experimental designs.

Identifying sites to cover the spatial variability and extent of a regional- to continental-scale question is an important first step that will assist with many of the research challenges, but filling spatial gaps alone is not sufficient to link networks and facilitate regional-to continental scale scientific endeavors. Additional measures must be taken to make sites interoperable and the data collected, accessible and comparable for end-users. Because sites from different network types focus on different temporal, spatial, structural, and functional aspects of ecosystems, data manipulation will likely be required before analyses can be conducted.

There are four components needed for data interoperability: (1) objectives need to be mapped to the scientific, technical and design elements in order to define the overlap and detail of scientific scope. This mapping includes details of space and time scales, defining the expected signal-to-noise ratio of the desired phenomena, and other overlapping scientific bounds. (2) Measurements need to be traceable to known national or international standards, first principles, or best community practices, and software and active management programs are needed to be in place to track and manage this traceability. (3) Algorithm processes and procedures that aggregate or transform source data into derived data products need to be documented. Knowing the similarities and differences in the process to create a data product and its associated uncertainties allows for the direct statistical comparison and for these data products to be used for prognostic activities, e.g., data assimilation and Bayesian technics that require uncertainty estimates a priori. (4) Standardized data and metadata formats and any other soft- or hardware capacity that fosters the ease of assessing, exploring, and analyzing data need to be openly accessible to the broader community.

Cultural changes will be needed for this über network to be successful. Data sharing and collaboration will need to be rewarded as part of open science (Wolkovich et al. 2012, Hampton et al. 2013). Institutional and cultural barriers must be overcome as well as geopolitical constraints among countries that comprise continents (Vargas et al. 2012). Funding agencies will need to prioritize broad-scale ecology, and interdisciplinary and international directorates will need to work together in joint initiatives. Ecologists can learn from the experience of other disciplines, in particular particle physics and genomics, where data are routinely shared as a result of a cultural shift that occurred regardless of journal or funding requirements or political affiliation (Strasser 2008, Hesla 2012). In these disciplines, collaboration among scientists is viewed as essential to make rapid advances and scientific discovery, in particular as the types, amounts, and rate and quality of data delivery are expected to increase (Hey and Trefethen 2005). Similar collaboration as part of open science will be needed for the success of continental-scale ecology, as well as more generally for the field of ecology, for advances in global change research (Wolkovich et al. 2012).

CONCLUSIONS

At regional to continental scales, natural, managed, and human-dominated ecosystems are subject to complex, interacting drivers that play out over extended periods of time and space. There are numerous calls for establishing a broader understanding of broad-scale environmental sciences across time and space (National Research Council 2001, Schimel et al. 2011), and to address new areas of science that can contribute towards addressing future societal needs (National Research Council 2011, Suresh 2012, Vargas et al. 2012, Holdren 2013*a*, United States Global Change Research Program 2013). In particular, developing better regional-to-continental-to-global scientific understanding is needed for Societal Benefit Areas (SBA; i.e., Agriculture, Biodiversity, Climate, Disasters, Ecosystems, Energy, Human Health, Water, and Weather) (Holdren 2013*b*, International Council for Science 2013, Group on Earth Observations 2012). No single observatory or science project has the capacity or scope to address all the environmental grand challenge questions (National Research Council 2001) or SBAs alone. Given the dynamics of these systems, it should not be expected that a single observatory network will have an all encompassing capacity to address these questions. We describe how a research infrastructure that integrates data, information, and expertise from individual sites and sites within networks can address many of the challenges facing regional- to continental-scale ecology. Cultural changes that promote and reward open science will maximize the effectiveness of organized research networks and facilitate meeting challenges in broad-scale ecology. Ultimately, scientists must network across institutional boundaries in order to tap and expand upon these existing network infrastructures before these investments can address critical regional- to continental-scale research questions and needs.

ACKNOWLEDGMENTS

Funding was provided by the National Science Foundation (NSF) to New Mexico State University (DEB-0618210, EF-1065699, DEB-1065699). D. P. C. Peters and K. M. Havstad acknowledge the USDA Agricultural Research Service (#6235-11210-007), and H. W. Loescher and M. D. SanClements acknowledge the NSF (DBI-0752017) for their ongoing support. We thank Dr. E. T. Borer for providing the NutNet map, and Dr. Jin Yao and Stacey P. Scroggs for assistance with the figures. The National Ecological Observatory Network (NEON) is a project funded by the NSF and managed under cooperative agreement by NEON, Inc. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

LITERATURE CITED

Adler, P. B., et al. 2011. Productivity is a poor predictor of plant species richness. Science 333:1750–1753.

Albertson, F. W., and J. E. Weaver. 1942. History of the vegetation of western Kansas during seven years of continuous drought. Ecological Monographs 12:23–51.

Baker, K. S., B. J. Benson, D. L. Henshaw, D. Blodgett, J. H. Porter, and S. G. Stafford. 2000. Evolution of a multisite network information system: the LTER information management paradigm. BioScience 50:963–978.

Barbier, E. B. 2006. Natural barriers to natural disasters: replanting mangroves after the tsunami. Frontiers in Ecology and the Environment 4:124–131.

Bestelmeyer, B. T., et al. 2011. Analysis of abrupt transitions in ecological systems. Ecosphere 2:art129.

Borer, E. T., W. S. Harpole, P. B. Adler, E. M. Lind, J. L. Orrock, E. W. Seabloom, and M. D. Smith. 2014. Finding generality in ecology: a model for globally distributed experiments. Methods in Ecology and Evolution 5:65–73.

Chatenoux, B., and P. Peduzzi. 2007. Impacts from the 2004 Indian Ocean tsunami: analyzing the potential protecting role of environmental features. Natural Hazards 40:289–304.

Chepil, W. S. 1957. Dust Bowl: Causes and effects. Journal of Soil and Water Conservation 12:108–111.

Choobari, O. A., P. Zawar-Reza, and A. Sturman. 2014. The global distribution of mineral dust and its impacts on the climate system: a review. Atmospheric Research 138:152–165.

Clark, D. B., and D. A. Clark. 2000. Landscape-scale variation in forest structure and biomass in a tropical rain forest. Forest Ecology and Management 137:185–198.

Cook, B. I., R. L. Miller, and R. Seager. 2009. Amplification of the North American "Dust Bowl" drought through human-induced land degradation. Proceedings of the National Academy of Sciences 106:4997–5001.

Creamean, J. M., et al. 2013. Dust and biological aerosols from the Sahara and Asia influence precipitation in the Western U.S. Science 339:1572–1578.

Crowl, T., R. Parmenter, and T. Crist. 2008. The spread of invasive species and infectious disease as drivers of ecosystem change. Frontiers in Ecology and the Environment 6:238–246.

Deck, J., et al. 2013. Clarifying concepts and terms in biodiversity informatics. Standards in Genomics 8(2):352–359.

Egan, T. 2006. The worst hard time: the untold story of those who survived the Great American Dust Bowl. Houghton Mifflin. New York, New York, USA.

Elmendorf, S. C., et al. 2012. Global assessment of experimental climate warming on tundra vegetation: heterogeneity over space and time. Ecology Letters 15:164–175.

Fahey, T. J., and A. K. Knapp. 2007. Principles and standards for measuring primary production. Oxford University Press, Oxford, UK.

Field, J. P., J. Belnap, D. D. Breshears, J. C. Neff, G. S. Okin, J. J. Whicker, T. H. Painter, S. Ravi, M. C. Reheis, and R. L. Reynolds. 2010. The ecology of dust. Frontiers in Ecology and the Environment 8:423–430.

Fountain, A. G., et al. 2012. The disappearing cryosphere: impacts and ecosystem responses to rapid cryosphere loss. BioScience 62:405–415.

Fraser, L. H., et al. 2013. Coordinated distributed experiments: an emerging tool for testing global hypotheses in ecology and environmental science. Frontiers in Ecology and the Environment 11:147–155.

Gill, T. E., T. W. Collins, and D. J. Novlan. 2010. Differential impacts of flash flooding across the Paso del Norte. Southwest Hydrology 9:20–21.

Gottfried, M., et al. 2012. Continent-wide response of mountain vegetation to climate change. Nature Climate Change 2:111–115.

Grace, J. B., et al. 2012. Response to comments on "productivity is a poor predictor of plant species richness". Science 335:1441.

Grimm, N. B., S. H. Faeth, N. E. Golubiewski, C. L. Redman, J. Wu, X. Bai, and J. M. Briggs. 2005. Global change and the ecology of cities. Science 319:756–760.

Grimm, N. B., D. Foster, P. Groffman, J. M. Grove, C. S. Hopkinson, K. J. Nadelhoffer, D. E. Pataki, and D. P. C. Peters. 2008. The changing landscape: ecosystem responses to urbanization and pollution across climatic and societal gradients. Frontiers in Ecology and the Environment 6:264–272.

Group on Earth Observations. 2012. GEO 2012-2015 Work Plan. http://www.earthobservations.org/documents/work%20plan/GEO%202012-2015%20Work%20Plan_Rev2.pdf

Guo, Q., Z. M. Hu, S. G. Li, X. R. Li, X. M. Sun, and G. R. Yu. 2012. Spatial variation in aboveground net primary productivity along a climate gradient in Eurasian temperate grassland: effects of mean annual precipitation and its seasonal distribution. Global Change Biology 18:3624–3631.

Hampton, S. E., C. A. Strasser, J. J. Tewksbury, W. K. Gram, A. E. Budden, A. L. Batcheller, C. S. Duke, and J. H. Porter. 2013. Big data and the future of ecology. Frontiers in Ecology and the Environment 11:156–162.

Hasselquist, N. J., R. Vargas, and M. F. Allen. 2010. Using soil sensing technology to examine interactions and controls between ectomycorrhizal growth and environmental factors on soil CO_2 dynamics. Plant and Soil 331:17–29.

Havstad, K. M., L. F. Huenneke, and W. H. Schlesinger. 2006. Structure and Function of a Chihuahuan

Desert Ecosystem. Oxford University Press, New York, New York, USA.

Herrick, J. E., V. C. Lessard, K. E. Spaeth, P. L. Shaver, R. S. Dayton, D. A. Pyke, L. Jolley, and J. J. Goebel. 2010. National ecosystem assessment supported by science and local knowledge. Frontiers in Ecology and the Environment 8:403–408.

Herweiger, C., R. Seager, and E. Cook. 2006. North American droughts of the mid to late nineteenth century: a history, simulation and implication for Medieval drought. Holocene 15:159–171.

Hesla, L. August 2012. Particle physics tames big data. http://www.symmetrymagazine.org/article/august-2012/particle-physics-tames-big-data

Hey, T., and A. E. Trefethen. 2005. Cyberinfrastructure for e-Science. Science 308:817–821.

Holdren, J. P. 2013*a*. Memorandum for the Heads of Executive Departments and Agencies: Increasing access to the results of federally funded scientific research. Executive Office of the President, Office of Science and Technology Policy.

Holdren, J. P. 2013*b*. National strategy for civil earth observations. Executive Office of the President National Science and Technology Council, Office of Science and Technology Policy.

Hollister, J. W., and H. A. Walker. 2007. Beyond data: reproducible research in ecology and environmental science. Frontiers in Ecology and the Environment 5:11–12.

Hsu, J. S., J. Powell, and P. B. Adler. 2012. Sensitivity of mean annual primary production to precipitation. Global Change Biology 18:2246–2255.

Huxman, T. E., et al. 2004. Convergence across biomes to a common rain-use efficiency. Nature 429:651–654.

International Council for Science. 2013. Future Earth research for global sustainability: Draft report. http://www.icsu.org/future-earth/media-centre/relevant_publications/FutureEarthdraftinitialdesignreport.pdf

IPCC. 2012. Managing the risks of extreme events and disasters to advance climate change adaptation: a special report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, New York, USA.

Iván, G., and V. Grolmusz. 2011. When the Web meets the cell: using personalized PageRank for analyzing protein interaction networks. Bioinformatics 27:405–407.

Jones, J. A., et al. 2012. Ecosystem processes and human influences regulate streamflow response to climate change at Long-Term Ecological Research sites. BioScience 62:390–404.

Jones, M. B., M. P. Schildhauer, O. J. Reichman, and S. Bowers. 2006. The new bioinformatics: integrating ecological data from the gene to the biosphere. Annual Review of Ecology, Evolution, and Systematics 37:519–544.

Kampe, T. U., B. R. Johnson, M. Kuester, and M. Keller. 2010. NEON: the first continental-scale ecological observatory with airborne remote sensing of vegetation canopy biochemistry and structure. Journal of Applied Remote Sensing 4:043510.

Kao, R. H., et al. 2012. NEON terrestrial field observations: designing continental-scale, standardized sampling. Ecosphere 3:art115.

Keller, M., D. S. Schimel, W. W. Hargrove, and F. M. Hoffman. 2008. A continental strategy for the National Ecological Observatory Network. Frontiers in Ecology and the Environment 6:282–284.

Kerr, R. A. 2013. Geophysical exploration linking deep Earth and backyard geology. Science 340:1283–1285.

Killeen, T., M. Uhle, and B. van der Pluijm. 2012. The International Opportunities Fund for global change research. Eos Transactions American Geophysical Union 93(28):257.

Knapp, A. K., and M. D. Smith. 2001. Variation among biomes in temporal dynamics of aboveground primary production. Science 291:481–484.

Knapp, A. K., M. D. Smith, S. E. Hobbie, S. L. Collins, and T. J. Fahey. 2012. Past, present, and future roles of long-term experiments in the LTER Network. BioScience 62:377–389.

Ladd, B., S. W. Laffan, W. Amelung, P. L. Peri, L. C. R. Silva, P. Gervassi, S. P. Bonser, M. Navall, and D. Sheil. 2013. Estimate of soil carbon concentration in tropical and temperate forest and woodland from available GIS data on three continents. Global Ecology and Biogeography 22:461–469.

Laney, C. M., K. S. Baker, D. P. C. Peters, and K. W. Ramsey. 2013. Recommendations for data accessibility. Pages 216–225 *in* D. P. C. Peters et al., editors. Long-term trends in ecological systems. a basis for understanding responses to global change. Technical Bulletin No. 1931. U.S. Department of Agriculture, Washington, D.C., USA.

Lauenroth, W. K., and O. E. Sala. 1992. Long-term forage production of North American shortgrass steppe. Ecological Applications 2:397–403.

Lehner, B., P. Döll, J. Alcamo, T. Henrichs, and F. Kaspar. 2006. Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis. Climatic Change 75:273–299.

Le Houérou, H. N., and C. H. Hoste. 1977. Rangeland production and annual rainfall relations in Mediterranean Basin and in African Sahelo-Sudanian zone. Journal of Range Management 30:181–189.

Madin, J. S., S. Bowers, M. P. Schildhauer, and M. P. Jones. 2008. Advancing ecological research with ontologies. Trends in Ecology and Evolution 23:159–168.

Marshall, J., J. Blair, D. P. C. Peters, G. S. Okin, R. Rango, and M. Williams. 2008. Predicting and understanding ecosystem responses to climate change at continental scales. Frontiers in Ecology and the Environment 6:273–280.

Mattice, W. A. 1935. Dust storms, November 1933 to May 1934. Monthly Weather Review 63:53–55.

McCormick, M. P., L. W. Thomason, and C. R. Trepte. 1995. Atmospheric effects of the Mt Pinatubo eruption. Nature 373:399–404.

Michener, W. K., and M. B. Jones. 2012. Ecoinformatics: supporting ecology as a data-intensive science. Trends in Ecology and Evolution 27:85–93.

Miller, J. D., B. M. Collins, J. A. Lutz, S. L. Stephens, J. W. van Wagtendonk, and D. A. Yasuda. 2012. Differences in wildfires among ecoregions and land management agencies in the Sierra Nevada region, California, USA. Ecosphere 3:art80.

Moran, M. S., D. P. C. Peters, M. P. McClaran, M. H. Nichols, and M. B. Adams. 2008. Long-term data collection at USDA experimental sites for studies of ecohydrology. Ecohydrology 1:377–393.

Myster, R. W. 2012. Ecotones between forest and grassland. Springer, New York, New York, USA.

National Climate Assessment. 2011. Climate change impacts and responses: societal indicators for the National Climate Assessment. National Climate Assessment Report Series. Volume 5c. United States Global Change Research Program, Washington, D.C., USA.

National Research Council. 2001. Grand challenges in environmental sciences. National Academies Press, Washington, D.C., USA.

National Research Council. 2003. NEON: addressing the nation's environmental challenges. National Academies Press, Washington, D.C., USA.

National Research Council. 2011. A review of the U.S. Global Change Research Program's Draft Strategic Plan. National Academies Press, Washington, D.C., USA.

Okal, E. A., and C. E. Synolakis. 2008. Far-field tsunami hazard from mega-thrust earthquakes in the Indian Ocean. Geophysical Journal International 172:995–1015.

Palmer, M. W., D. B. Clark, and D. A. Clark. 2000. Is the number of tree species in small tropical forest plots nonrandom? Community Ecology 1:95–101.

Parton, W. J., W. L. Silver, I. C. Burke, L. Grassens, M. E. Harmon, W. S. Currie, J. Y. King, E. C. Adair, L. A. Brandt, S. C. Hart, and B. Fasth. 2007. Global-scale similarities in nitrogen release patterns during long-term decomposition. Science 315:361–364.

Perry, K., T. Cahill, R. Eldred, D. D. Dutcher, and T. E. Gill. 1997. Long-range transport of North African dust to the eastern United States. Journal of Geophysical Research: Atmospheres 102:11225–11238.

Peters, D. P. C. 2010. Accessible ecology: synthesis of the long, deep, and broad. Trends in Ecology and Evolution 25:592–601.

Peters, D. P. C., J. Belnap, S. L. Collins, J. Ludwig, J. Paruelo, and T. Hoffman. 2012*a*. How can science be general yet specific: the conundrum of range science in the 21st century. Rangeland Ecology and Management 65:613–622.

Peters, D. P. C., P. M. Groffman, K. J. Nadelhoffer, N. B. Grimm, S. L. Collins, W. K. Michener, and M. A. Huston. 2008. Living in an increasingly connected world: a framework for continental-scale environmental science. Frontiers in Ecology and the Environment 6:229–237.

Peters, D. P. C., R. A. Pielke, B. T. Bestelmeyer, C. D. Allen, S. Munson-McGee, and K. M. Havstad. 2004*a*. Cross-scale interactions, nonlinearities, and forecasting catastrophic events. Proceedings of the National Academy of Sciences USA 101:15130–15135.

Peters, D. P. C., D. L. Urban, R. D. Gardner, D. D. Breshears, and J. E. Herrick. 2004*b*. Strategies for ecological extrapolation. Oikos 106:627–636.

Peters, D. P. C., J. Yao, O. E. Sala, and J. P. Anderson. 2012*b*. Directional climate change and potential reversal of desertification in arid and semiarid ecosystems. Global Change Biology 18:151–163.

Peters, D. P. C., et al. 2013. Long-term trends in ecological systems: a basis for understanding responses to global change. Technical Bulletin No. 1931. U.S. Department of Agriculture, Wasington, D.C., USA.

Ponce-Campos, G. E., et al. 2013. Ecosystem resilience despite large-scale altered hydroclimate conditions. Nature 494:349–352.

Porter, J. H., E. Nagy, T. K. Kratz, P. C. Hanson, S. C. Collins, and P. W. Arzberger. 2009. New eyes on the world: advanced sensors for ecology. BioScience 59:385–397.

Pottie, G. J., and W. J. Kaiser. 2000. Wireless integrated network sensors. Communications of the ACN 23:51–58.

President's Council of Advisors on Science and Technology. 2011. Report to the President: Sustaining Environmental Capital: Protecting Society and the Economy. Office of Science, Technology and Policy, Washington, D.C., USA.

Reichman, O. J., M. B. Jones, and M. P. Schildhauer. 2011. Challenges and opportunities of open data in ecology. Science 331:703–705.

Rhoades, C. C., J. H. McCutchan, Jr., L. A. Cooper, D. Clow, T. M. J. Detmer, S. Briggs, J. D. Stednick, T. T. Veblen, R. M. Ertz, G. E. Likens, and W. M. Lewis, Jr. 2013. Biogeochemistry of beetle-killed forests: explaining a weak nitrate response. Proceedings of the National Academy of Sciences USA 110:1756–1760.

Robertson, G. P., D. C. Coleman, C. S. Bledsoe, and P. Sollins. 1999. Standard soil methods for long-term ecological research. Oxford University Press, Oxford, UK.

Robertson, G. P., et al. 2012. Long-term ecological research in a human-dominated world. BioScience 62:342–353.

Sala, O. E., L. A. Gherardi, L. Reichmann, L. Jobbágy, and D. P. C. Peters. 2012. Legacies of precipitation fluctuations on primary production: theory and data synthesis. Philosophical Transactions of the Royal Society B 367:3135–3144.

Sala, O. E., W. J. Parton, L. A. Loyce, and W. K. Lauenroth. 1988. Primary production of the central grassland region of the United States: spatial pattern and major controls. Ecology 69:40–45.

Schimel, D., M. Keller, S. Berukoff, R. Kao, H. W. Loescher, H. Powell, T. Kampe, D. Moore, and W. Gram. 2011. NEON science strategy: enabling continental-scale ecological forecasting. NEON, Boulder, Colorado, USA.

Schubert, S. D., M. J. Suarez, P. J. Pegion, R. D. Koster, and J. T. Bacmeister. 2004. On the cause of the 1930s Dust Bowl. Science 303:1855–1859.

Schwartz, M. D., J. L. Betancourt, and J. F. Weltzin. 2012. From Caprio's lilacs to the USA National Phenology Network. Frontiers in Ecology and the Environment 10:324–327.

Seager, R., et al. 2007. Model Projections of an imminent transition to a more arid climate in southwestern North America. Science 316:1181–1184.

Self, S. 2006. The effects and consequences of very large explosive volcanic eruptions. Philosophical Transactions of the Royal Society A 364:2073–2097.

Sierra, C. A., H. W. Loescher, M. E. Harmon, A. D. Richardson, D. Y. Hollinger, and S. S. Perakis. 2009. Interannual variation of carbon fluxes from a tropical, a temperate, and a boreal evergreen forest: the role of forest dynamics and climate. Ecology 90:2711–2723.

Strasser, B. J. 2008. GenBank: natural history in the 21st century. Science 322:537–538.

Suresh, S. 2012. Research funding: Global challenges need global solutions. Nature 490:337–338.

Taylor, J., and H. W. Loescher. 2013. Automated quality control methods for sensor data: a novel observatory approach. Biogeosciences 10:1–15.

Trenberth, K. E., et al. 2007. Observations: surface and atmospheric climate change. Pages 235–336 *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. Climate Change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

United States Global Change Research Program. 2013. Climate assessment report. Third assessment.

Vargas, R., H. W. Loescher, T. Arredondo, E. Huber-Sannwald, R. Lara-Lara, and E. A. Yépez. 2012. Opportunities for advancing carbon cycle science in Mexico: towards a continental scale understanding. Environmental Science and Policy 12:84–93.

Vision, T. J. 2010. Open data and the social contract of scientific publishing. BioScience 60:330–331.

Weaver, J. E., and F. W. Albertson. 1936. Effects of the great drought on the prairies of Iowa, Nebraska, and Kansas. Ecology 4:567–639.

Whitlock, M. C. 2011. Data archiving in ecology and evolution: best practices. Trends Ecology Evolution 26:61–65.

Whittaker, R. H. 1975. Communities and ecosystems. Second edition. Macmillan, New York, New York, USA.

Williamson, C. E., W. Dodds, T. K. Kratz, and M. A. Palmer. 2008. Lakes and streams as sentinels of environmental change in terrestrial and atmospheric processes. Frontiers in Ecology and the Environment 6:247–254.

Wolkovich, E. M., J. Regetz, and M. I. O'Connor. 2012. Advances in global change research require open science by individual researchers. Global Change Biology 18:2102–2110.

Worster, D. 1979. Dust Bowl: The Southern Plains in the 1930s. Oxford University Press, New York, New York, USA.

Yao, J., O. E. Sala, and D. P. C. Peters. 2013. Cross-site studies "by design": experiments and observations that provide new insights. Pages 72–80 *in* D. P. C. Peters, et al., editors. Long-term trends in ecological systems. a basis for understanding responses to global change. Technical Bulletin No. 1931. U.S. Department of Agriculture, Washington, D.C., USA.

Yoshioka, M., N. M. Mahowald, A. J. Conley, W. D. Collins, D. W. Fillmore, C. S. Zender, and D. B. Coleman. 2007. Impact of desert dust radiative forcing on Sahel precipitation: Relative importance of dust compared to sea surface temperature variations, vegetation changes, and greenhouse gas warming. Journal of Climate 20:1445–1467.

Yu, Z., S. Liu, J. Wang, P. Sun, W. Liu, and D. S. Hartley. 2013. Effects of seasonal snow on the growing season of temperate vegetation in China. Global Change Biology 19:2182–2195.

Zhang, F., J. M. Chen, J. Chen, C. M. Gough, T. A. Martin, and D. Dragoni. 2012. Evaluating spatial and temporal patterns of MODIS GPP over the conterminous U.S. against flux measurements and a process model. Remote Sensing of Environment 124:717–729.