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Accessible ecology: synthesis of the long, deep, and broad

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Large volumes of data have been collected to document the many ways that ecological systems are responding to changing environmental drivers. A general buy-in on solutions to these problems can be reached only if these and future data are made easily accessible to and understood by a broad audience that includes the public, decision-makers, and other scientists. A developing framework for synthesis is reviewed that integrates three main strategies of ecological research (long-term studies; short-term, process-based studies; and broad-scale observations) with derived data products and additional sources of knowledge. This framework focuses on making data from multiple sources and disciplines easily understood by many, a prerequisite for finding synthetic solutions and predicting future dynamics in a changing world.

Challenges to synthesis

Dramatic changes in climate, land cover, and habitat availability have occurred over the past several centuries influencing every ecosystem on Earth [1,2]. Large amounts of data, and in particular observations over long time periods, have been collected to document changes, which include shifts in species dominance, loss of biodiversity, and reductions in clean air and water quality and quantity [3–5]. Solutions to environmental problems are elusive, in large part because much of the data have not been synthesized and remain inaccessible to a broad audience [6,7]. The complex nature of environmental problems requires that different types of data from multiple sources and disciplines be integrated [8], yet the sheer volume and nature of the data make it a challenge to ensure accessibility in a coherent, easy-to-understand format. Most data are too technical or complicated for general use [7], and many data are posted online in non-standard formats. Inaccuracies in the data and missing descriptive metadata further limit accessibility [9]. Some complex data have been distilled into useful formats for non-scientists [1,7], but questions can arise as to how the data were interpreted or analyzed (e.g. http://www.eenews.net/public/climatewire/2009/11/24/1). Standardization, simplification, and integration are required before data can be visualized, analyzed, and synthesized to generate new understanding [10,11].

Given that the Earth is changing at faster rates and in different ways than expected, there is a critical need to make existing and future data accessible in a format that the public and decision-makers can understand [12]. Accessible data are also needed by scientists to guide the strategic collection of additional data, and in synthesis efforts to yield new knowledge, insights, generalities, and solutions [8,13,14]. The continued collection of long-term data [15] and the emergence of observatories of multiple sites collecting a large suite of standardized data, such as the National Ecological Observatory Network (NEON), will magnify the problem further [16]; thus, reinforcing the critical need to improve data accessibility and utility within a synthesis framework that is sufficiently flexible, expandable, and robust to handle these future data sources.

Here, I review three general strategies associated with ecological research (long-term studies; short-term, pattern-process studies for deep understanding; and observation networks of sites for broad-scale patterns) commonly used to investigate ecological responses to a changing environment. Each strategy provides unique insights with important contributions to ecological knowledge, yet each also has scientific limitations and challenges to data accessibility and synthesis. Although examples of each strategy are drawn primarily from US-funded research, the principles and challenges apply globally [17,18]. Then, I describe a framework for synthesis being developed to make different types and sources of data from these strategies accessible with utility to a broad audience. I draw upon insights from the EcoTrends Project (http://www.ecotrends.info) to illustrate the application of this framework for a range of ecosystems found globally (terrestrial, aquatic, coastal, and urban) [19]. Finally, I emphasize new research directions to improve data accessibility and synthesis, and to provide new ecological knowledge for forecasting future ecosystem dynamics.

Ecology of the 'long'

The importance of long-term data to ecological knowledge has become increasingly apparent as the length of data records has increased [20]. In the US, studies of ecosystems started in the early 1900 s when forest, watershed, and rangeland sites were established, primarily by the United States Department of Agriculture (USDA) [21,22]. The research was both observation-based and experimental using manipulations related to management, such as altered fire frequency. Many long-term ecological sites now exist, including those in the Long Term Ecological

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Research Program (LTER) that began in 1980 [23] and sites studied by individuals or groups [24,25].

The 'ecology of the long' [15] complements detailed, process-based studies conducted over short time periods within a single ecosystem type (see next section: Ecology of the 'deep'). Ecological systems vary through time as environmental conditions change. Long-term data are needed to assess the rate and direction of change, to distinguish directional trends from short-term variability, and to determine effects of infrequent, yet extreme events and time lags in response [26–30]. Long-term data can inform government policy. For example, data showed an increase in acid rain in North America in the 1970 s [31], and that acid rain had negative impacts on forest growth and surface water chemistry [32,33]. These results led to the 1990 Amendments to the Clean Air Act which reduced sulfur dioxide emissions and sulfate concentrations in precipitation [34,35].

Comparisons of trends in drivers with ecological responses can infer causal relationships. For example, long-term studies off the Antarctic coast show strong correlations among drivers and system dynamics, and a state change from dominance by Adélie penguins to Gentoo and Chinstrap penguins (Figure 1). Now, short-term, detailed studies of predator–prey relationships under variable conditions of sea ice are needed to determine where, when, and how phytoplankton biomass or sea ice (or their interactions) drive loss of Adélie penguins or if a different set of processes are shifting dominance between penguin species, although field experiments at the required scale are challenging to conduct in this system. These short-term studies will need to be effectively integrated with the existing long-term studies if a complete understanding is to be achieved.

Limitations

Long-term observations can lead to hypotheses about processes underlying patterns, but cannot identify the processes. More than one process can create the same pattern, multiple interacting processes can result in the pattern, and spurious relationships can result with no causative explanation between pattern and process. In addition, the relationship between patterns and the processes driving them can change with temporal or spatial scale [41]. Long-term studies create challenges to data accessibility in that the sampling frequency and intensity, and the spatial scale (e.g. plot size) can change through time with turnover in personnel and as funding levels vary. Methods can change

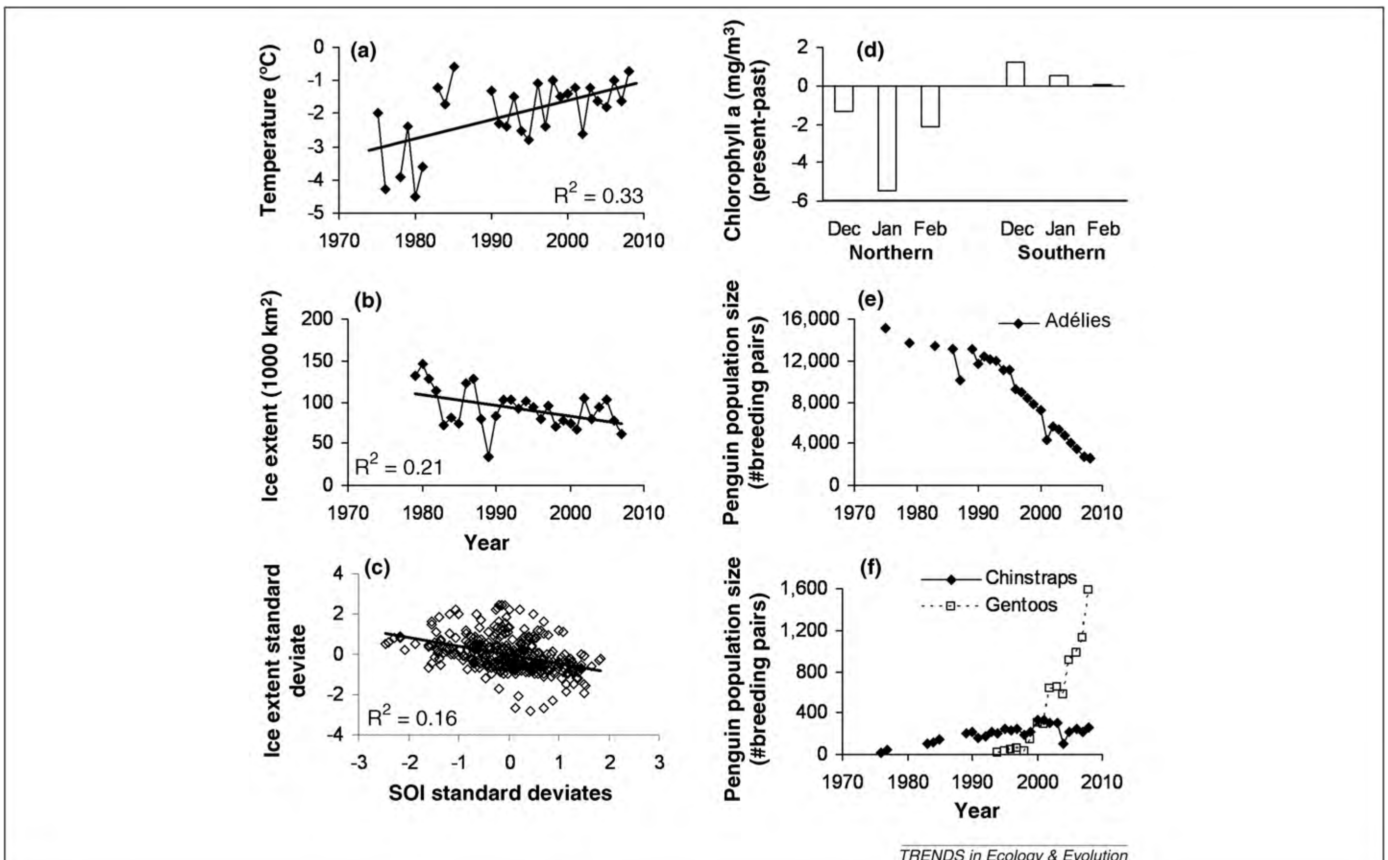

Figure 1. Long-term data for multiple drivers and ecological responses off the coast of the Western Antarctic Peninsula: **(a)** surface air temperatures have increased at some of the fastest recorded rates (temperature[°C] = –119 + 0.06 × Time[years]; R^2 = 0.33; p = 0.001) globally [36] (data from http://www.ecotrends.info). **(b)** Sea ice spatial extent has decreased significantly (ice extent[1000 km^2] = 2707 – 1.3 × Time[years]; R^2 = 0.21; p = 0.01) with a later advance and an earlier retreat of ice [37]. **(c)** Sea ice is related to the Southern Oscillation Index (SOI), and tends to advance during cooler La Nina periods, and retreat during warmer El Niño periods [38] (data from http://pal.lternet.edu shown as deviations from the mean: ice extent = –0.04 – 0.4 × SOI; R^2 = 0.16; $p < 0.0001$). **(d)** Phytoplankton biomass has shifted southward through time with decreases in the north (past: 1978–1986; present: 1998–2006) [39]. This shift in phytoplankton biomass is expected to reduce biomass of krill in the north, an important food source for Adélie penguins, **(e)** whose populations have been decreasing through time compared with **(f)** increases in populations of the ice-avoiding Gentoo and Chinstrap [40] (data from http://www.ecotrends.info). These patterns in drivers and biotic responses can be used to infer causal relationships, but identifying the key processes driving the state change between penguin species requires detailed studies of predator–prey relationships under multiple environmental conditions.

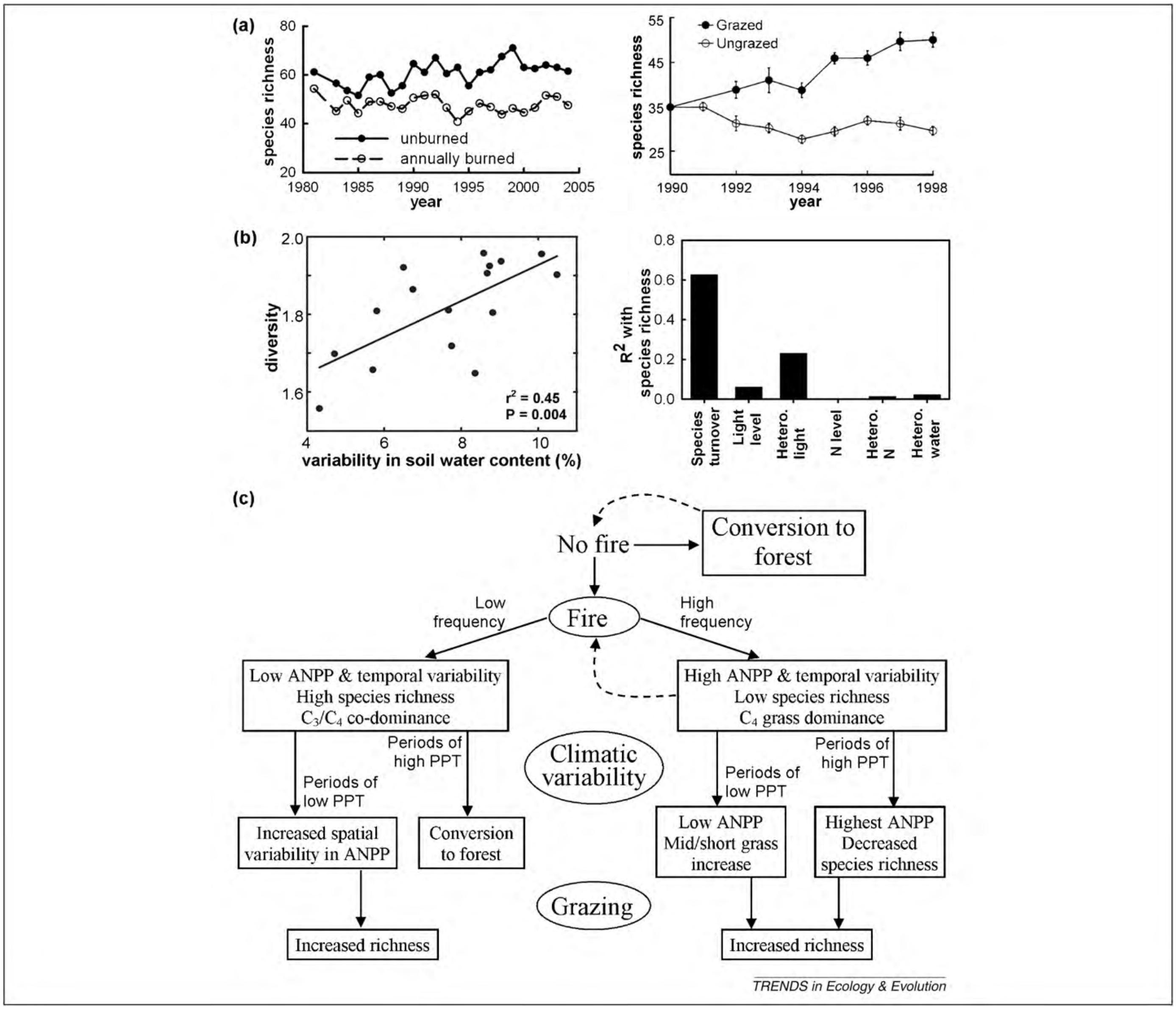

Figure 2. Deep understanding of tallgrass prairie at the Konza Prairie LTER site involves a suite of approaches. Short-term experiments are used to provide the mechanistic understanding for long-term observations, and a conceptual model is used to integrate the information. **(a)** Initial experiments focused on fire and grazing as historic drivers [51] and showed that [left] annual fire reduces plant species richness (updated from [52]) whereas [right] large herbivores (bison) increase plant and animal (not shown) species richness through time [53,54] (data from http://www.ecotrends.info). **(b)** [Left panel]: the hypothesis that variability in richness (and aboveground net primary production [ANPP], not shown) is related to variability in precipitation was tested using a short-term study where fewer, large rain events compared to natural rain events were added each year for four years [55]. This within- and between-year variability in rainfall increased variability in soil water with positive effects on plant diversity, a measure of species richness [55; Reprinted with permission from AAAS]. [Right panel]: short-term studies also showed that grazing increases spatial heterogeneity in light available to plants and increases turnover rate of species through time to result in higher species richness (redrawn from [56]) regardless of fire frequency [57]. **(c)** Results from these short- and long-term studies and others led to a conceptual framework used to: integrate information, test hypotheses, predict future dynamics, and strategically guide future research [redrawn and simplified from 50]. Extrapolation of these results to other sites in the tallgrass prairie requires information on spatial and temporal variability in both drivers and ecological responses.

with technological advances (e.g. automated sensors). Legacy data may not be well documented or in digital format, and variable names and file formats can change through time [9].

Ecology of the 'deep'

Place-based research conducted at one site or within one ecosystem type can provide deep understanding of processes underlying observed patterns [33]. Most studies are short-term (< 4 years), and some are conducted within a long-term context. These studies can also evaluate pattern–process relationships within and across scales [42–45]. Deep understanding is the hallmark of sites in the LTER Program where researchers test alternative hypotheses about drivers and responses using short-term experiments that lead logically from long-term observations, e.g. [46–49], and provide the mechanistic understanding for these observations.

For example, research at the Konza Prairie LTER site in Kansas has focused on teasing apart the relative importance of three drivers (fire, grazing, and climatic variability) in the dynamics of tallgrass prairie [50]. Short-term studies are used to examine the key mechanisms underlying long-term trends in observations. The LTER project began by observing grassland responses through time in response to manipulated fire frequency and grazing intensity by large native herbivores (bison) under natural climatic variability (Figure 2a). High temporal variability in plant species richness (Figure 2a [left]) was hypothesized to reflect variation in soil water as affected by precipitation. To test this hypothesis, within season rainfall variability (fewer, larger rain events) was manipulated with no increase in rainfall amount. Soil water dynamics increased in variability, both within and among years, with positive effects on richness (Figure 2b [left]). The increase in plant (Figure 2a [right]) and consumer richness (not shown) under grazing was explained using short-term sampling that showed greater spatial heterogeneity in light available to plants and greater turnover of species in grazed than ungrazed areas (Figure 2b [right]). As a result of these and many other studies (http://www.konza.ksu.edu), the Konza Prairie LTER program developed a conceptual framework that integrates the effects of fire, grazing, and climatic variability on dynamics of these grasslands (Figure 2c).

Limitations

Site-based studies conducted without long-term observations can have limited generality because the temporal and spatial contexts of the results are unknown. Extrapolation of results from one site to another or to the region as a whole requires information on spatial and temporal variability in drivers and responses [58]. Site-based studies are insufficient to understand how ecosystems are connected by interactions among air, water, and land at broad scales [58,59]. Accessibility of data can be challenging if standard protocols of collection, archival, and retrieval are not followed [60].

Ecology of the 'broad'

Observation networks of sites collecting similar data across broad spatial extents have been operational in the US since at least 1830 with the census of human populations (http://www/census.gov). The National Weather Service started collecting meteorological data in 1870 (http://www.nws.noaa.gov/), and streamflow has been monitored at some sites for over 100 years (http://waterdata.usgs.gov). Observation networks have emerged over the past decade to collect ecological data using standard protocols, including the Ocean Observatories Initiative (OOI) [61], WATERS (http://www.watersnet.org), and NEON [16]. Other networks are collections of sites with similar missions, such as the USDA Agricultural Research Service (ARS) rangeland sites and the Forest Service (FS) experi-

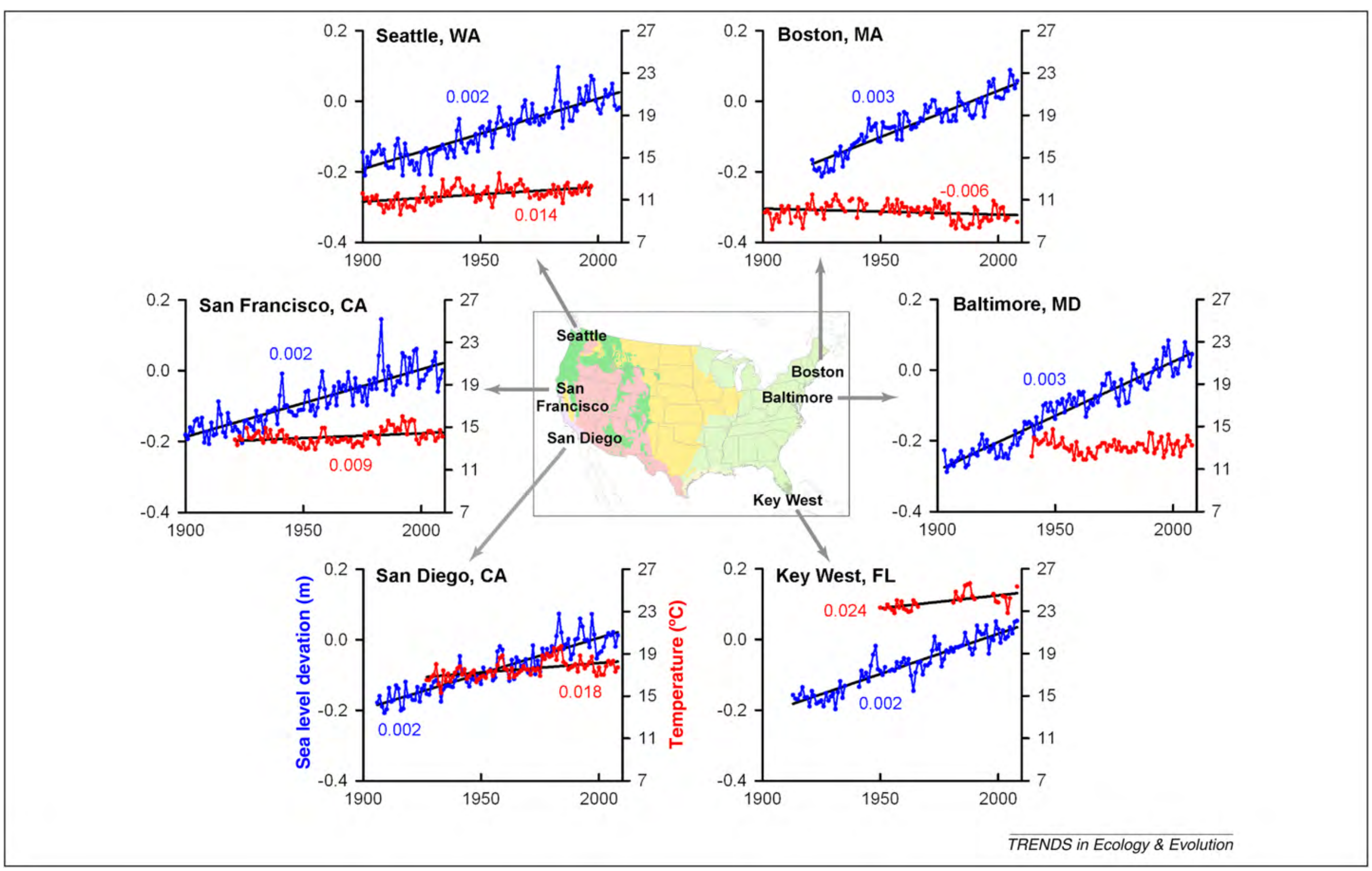

Figure 3. Broad-scale patterns can be observed using networks of sites either coordinated to collect similar data with standard protocols or integrated via the post-collection standardization of similar data. Sea level measured by the US Geological Survey (http://tidesandcurrents.noaa.gov/) using standard methods and instruments were used to calculate trends through time for cities along the east and west coasts of the country [19]. Long-term climate data obtained from a different source (https://www.ncdc.noaa.gov/) were used to calculate trends in average air temperature for the same cities or nearby research sites. Significant regression lines and slopes ($p \leq 0.05$) are shown in blue (sea level) and red (air temperature). All panels share the same y-axes labels of sea level and temperature. Comparing trends in the two drivers shows that most coastal sites have experienced an increase in sea level of 2–3 mm/y over the past 100 years. All west coast sites and Key West, FL have also experienced increasing air temperatures at rates of 0.01–0.02 °C /y (condensed data from http://www.ecotrends.info). Understanding the processes driving these patterns through time and predicting ecological responses requires detailed studies of mechanisms, both at individual sites and across environmental gradients, to capture variation in drivers and the biota.

mental forests, that collect data with site-specific methods; standardization is required before comparisons can be made [19,22].

In some cases, individuals collect data which, when combined, cover broad areas. The Global Population Dynamics Database contains animal and plant population data collected by individuals [62]. The National Phenology Network (NPN) contains data collected by citizen scientists using standard protocols [63]. Observing networks can be defined by regions or ecosystem types where individual projects with different protocols are integrated, such as the Global Lakes Ecological Observatory Network [64].

An integration of datasets from multiple networks is needed to compare continental-scale variation in multiple drivers, and to identify regions where multiple drivers are interacting to affect human and natural systems [19]. For example, sea level is increasing along the east and west coasts of the US, and surface air temperature is also increasing for sites on the west coast (Figure 3). Interactions between drivers may result in unexpected impacts on human populations and ecosystems located along the land–ocean margin [4,65].

Limitations

For observational networks that collect data with similar instruments at each site, standardized, aggregated data are accessible through a common web site. Comparisons of different kinds of data across networks require knowledge of and access to multiple web sites, and manual integration and analysis. These observing systems have limited ability to forecast dynamics without a long-term record of change for historical context, and a deep mechanistic understanding of pattern–process relationships across scales.

Linking the long, deep, and broad: a synthesis framework for understanding and prediction

Synthesis involves the integration of disparate data with existing concepts and theories to yield new knowledge, insights, and explanations [66]. Synthesis creates emergent knowledge through novel combinations of information [8]. A framework for synthesis is being developed where general patterns and underlying mechanisms are emerging from finding, blending, and integrating large volumes of data collected as part of the three strategies discussed above (Box 1). The framework is being developed to make complex data collected from different sources, locations, and disciplines easily accessible to and understood by a broad audience, and to develop new approaches and solutions to global change problems. This framework has points of contact with recent synthesis frameworks, and combines their key conceptual elements [10] with software tool development and training [67]. However, the focus on improving data and knowledge accessibility to a broad and diverse user community, with applications to policy, management, and personal actions, distinguishes this framework from others. This framework has five steps that address key limitations in the above three strategies.

First, data collected from different sources (individuals, sites, and networks) need to be assembled into digital formats where they are available to others (Box 1). These data can be from short-term experiments, long-term studies, and broad-scale observations guided by conceptual frameworks (Figures 1–3). This step may involve a number of technologies to: convert manually collected data into digital format, download data from sensors, verify data for accuracy (either manually or through automated value-checking routines), enter data into a user-specified database, release data to standard repositories, and post data onto the internet.

Second, these source data need to be standardized to allow their integration into a common database, either virtually with internet links or physically into a single database (Box 1). Although standard methods of data collection and analysis have been developed [68], and standard variable names and protocols are used by some research programs and networks [69], integrating data from different sources and disciplines remains a challenge that often requires post-collection standardization [9]. Even variables with well-defined standards, such as air temperature, can be collected in a variety of ways (e.g. at different heights) with different temporal resolutions (e.g. hourly, minimum and maximum daily). In some cases, such as observational networks, the data are already in a standard format, but only for one type of driver (e.g. climate variables); these data need to be integrated in a coherent way with ecological response data. In other cases, such as biotic data (plants, animals, and soils), the data are in a variety of formats that need to be standardized before integration [60]. Publishing details of methods, complete datasets, and metadata as extensions to scientific papers (e.g. Ecological Archives: http://esapubs.org/archive), and adhering to community-based standards [9] can provide information necessary for new analyses. As part of the standardization process, much can be learned about the structure of diverse datasets that can provide feedbacks to the data collection and assembly process of Step 1.

Third, the source data need to be condensed into simplified formats using aggregations in time and space to result in derived data products (Box 1). Source data from complex experimental designs are collected at very short time steps (days, months, and seasons) or small spatial extents (square meters and hectares) that make comparisons difficult. For example, rainfall data collected manually on an event basis or continuously through instrumentation need to be summed as monthly or annual totals. Biotic data often have a complex format needed to capture spatial and temporal variation in an ecological system [70]. For example, aboveground net primary production (ANPP) for a grassland site is often estimated by collecting biomass data seasonally by species in quadrats. ANPP is estimated by subtracting initial biomass by species (averaged across quadrats) from final average biomass. Summing ANPP by species results in site ANPP that can be compared across sites [19]. Additional derived data-products are needed to easily view patterns in the aggregated data, including X-Y graphs, maps, animations, and statistical results. The aggregation and analysis process will need new software tools and quantitative analyses, and training of scientists and information specialists to use and develop these tools.

Box 1. A framework for science-driven synthesis

A developing framework for synthesis includes five major steps and four classes of products that will result in making complicated data easily accessible for understanding and prediction by a broad audience (Figure I).

First, three strategies of ecological research (long-term studies; short-term, process-based studies; and broad-scale observations) result in large amounts of source data collected by individuals, sites, and networks of sites in a variety of formats, units, temporal and spatial resolutions, and degrees of complexity that need to be assembled. These data are often variable in their quality in terms of the degree to which they have been checked and corrected for errors.

Second, these diverse datasets need to undergo quality assurance and control, and to be standardized and integrated into one database, either a virtual database with internet links or a physical database. Much will be learned about the structure of diverse datasets that will provide important feedbacks to the data collection process.

Third, these data need to be converted into common aggregations to simplify their temporal and spatial resolutions that will allow comparison across sites and studies, and to promote synthesis. Derived data products need to be created, including X–Y graphs, maps, animations, and statistical results. The aggregation and analysis process will require new software tools and quantitative analyses, and training of scientists and information specialists to use and develop these tools.

Fourth, these derived data products need to be combined with other knowledge sources, new technologies, and approaches to promote new interpretations and synthesis of the data. A broad user community will be needed that includes individuals (e.g. scientists, land managers, citizen scientists, and information managers), networks of sites (e.g. LTER, USDA, and NEON), synthesis centers (e.g. National Center for Ecological Analysis and Synthesis [NCEAS, http://www.nceas.ucsb.edu/], National Evolutionary Synthesis Center [NESCent, http://www.nescent.org/], National Institute for Mathematical and Biological Synthesis [NIMBioS, http://www.nimbios.org/], and Powell Center; http://powellcenter.usgs.gov/), and state and federal agencies working together. These activities need to provide important feedbacks to the collection of additional data as well as to the development of tools and expertise for future analyses.

Fifth, these interpretations will need to inform policies, practices, and actions, and provide feedbacks to the collection of additional data. New technologies will need to be developed, and training of scientists and information managers in synthetic research will be needed to meet the challenges associated with synthesis.

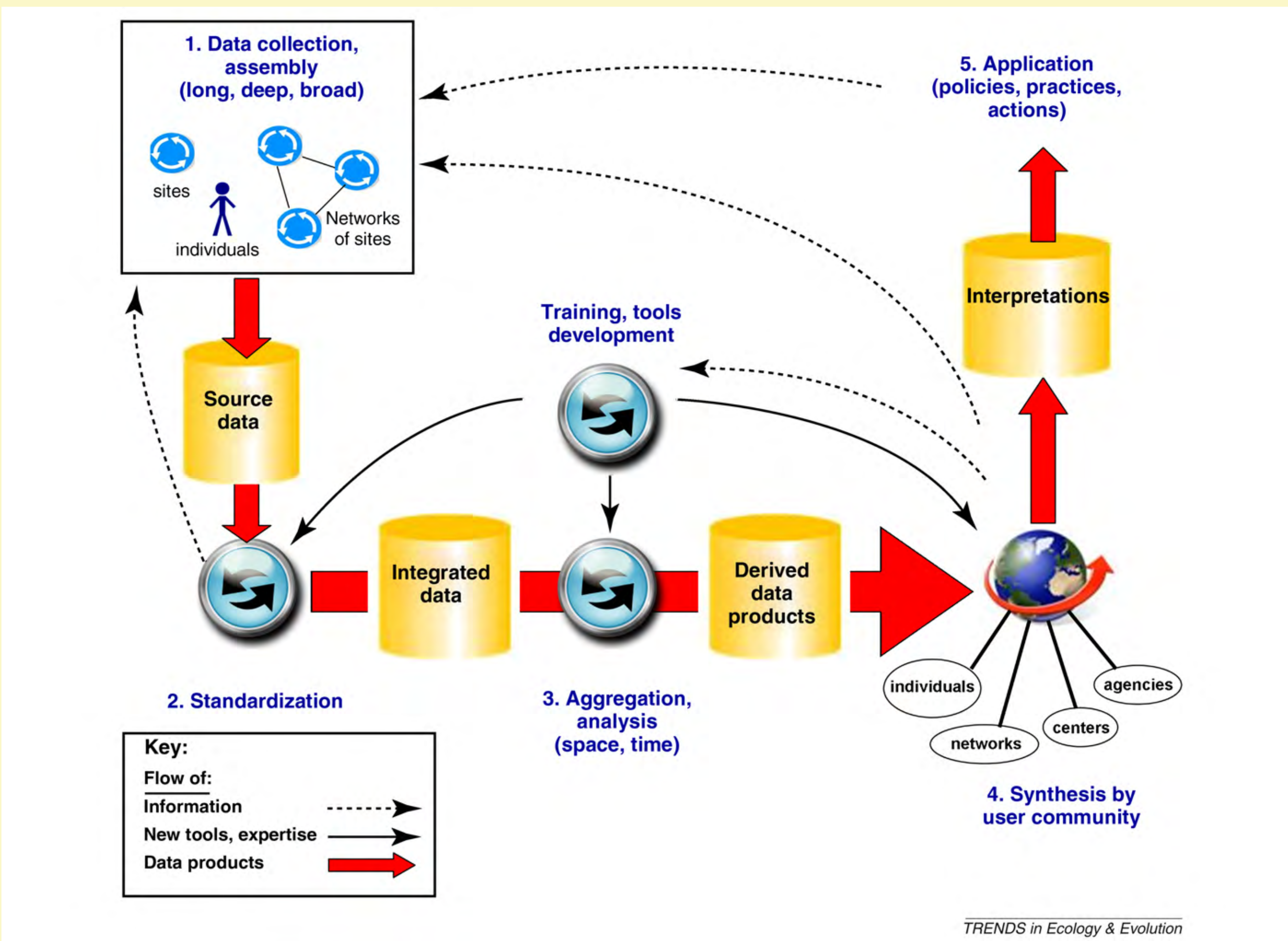

Figure I. A developing framework for synthesis includes five major steps (blue text) and four classes of products (yellow cylinders).

Although Steps 1–3 have been conducted on existing data in *post hoc* comparative analyses, e.g. [14,17,18], it is the fourth and fifth steps in this framework that have the potential to move synthesis to new quantitative levels required of current and future environmental problems.

Fourth, these derived data products need to be blended with other knowledge sources, new technologies, and approaches to promote new interpretations and syntheses by a broad user community (Box 1). Both traditional sources of knowledge (scientists, networks,

Box 2. EcoTrends as a first step towards a synthesis framework

Data from the EcoTrends Project (http://www.ecotrends.info) illustrate the first four steps of a developing framework for synthesis (Figure I). This project focuses on converting large volumes of *long-term data* from disparate sources into forms useful to others. Here, the data are used to address the following questions. How does continental- and regional-scale variation compare for trends in multiple drivers? What is the explanation for regional variation in drivers? What are the potential consequences of future changes in these drivers?

First, long-term data from three major sources were assembled: (1) broad-scale observation networks (National Climate Data Center [NCDC, http://www.ncdc.noaa.gov/], National Oceanic and Atmospheric Administration [NOAA, http://www.noaa.gov/], US Census Bureau [http://www.census.gov/], and National Atmospheric Deposition Program [NADP, http://nadp.sws.uiuc.edu/); (2) individual investigators; and (3) monitoring data from research sites, primarily LTER, and the USDA-FS and USDA-ARS.

Second, these diverse data were corrected for errors, and integrated into a common database using standard formats, units, and variable names.

Third, the standardized source data were converted into common aggregations to simplify the temporal and spatial resolutions of the data. These derived data were viewed as graphs to answer our first question: high spatial variation in trends across the continent does not reflect regional patterns [19,58]. Within Colorado, patterns are highly variable for two sites (Niwot Ridge alpine site in the Rocky Mountains [NWT] and the Shortgrass Steppe [SGS] semiarid grassland site in the eastern plains): temperature and population density are increasing at both sites, although at different rates. Precipitation is not changing (not shown), and nitrogen deposition is either increasing (NWT) or not changing (SGS) (data from http://www.ecotrends.info).

Fourth, multiple datasets were used to interpret the data. To answer our second question, we needed information about the spatial location of the sites relative to cities. Increases in nitrogen deposition at NWT are likely related to increases in human population density in the Denver area, and upslope conditions that bring rainfall and atmospheric nitrogen from Denver to the mountains [76]. By contrast, the SGS site is located east of cities with slower rates of population increase, resulting in no change in nitrogen deposition through time. To answer our third question required information about biotic sensitivity to nitrogen: alpine sites, such as NWT, may be more negatively affected by nitrogen deposition in the future, as a result of increasing deposition rates and their sensitivity to nitrogen inputs [77] compared to SGS grasslands that are insensitive to nitrogen inputs without additional water [78].

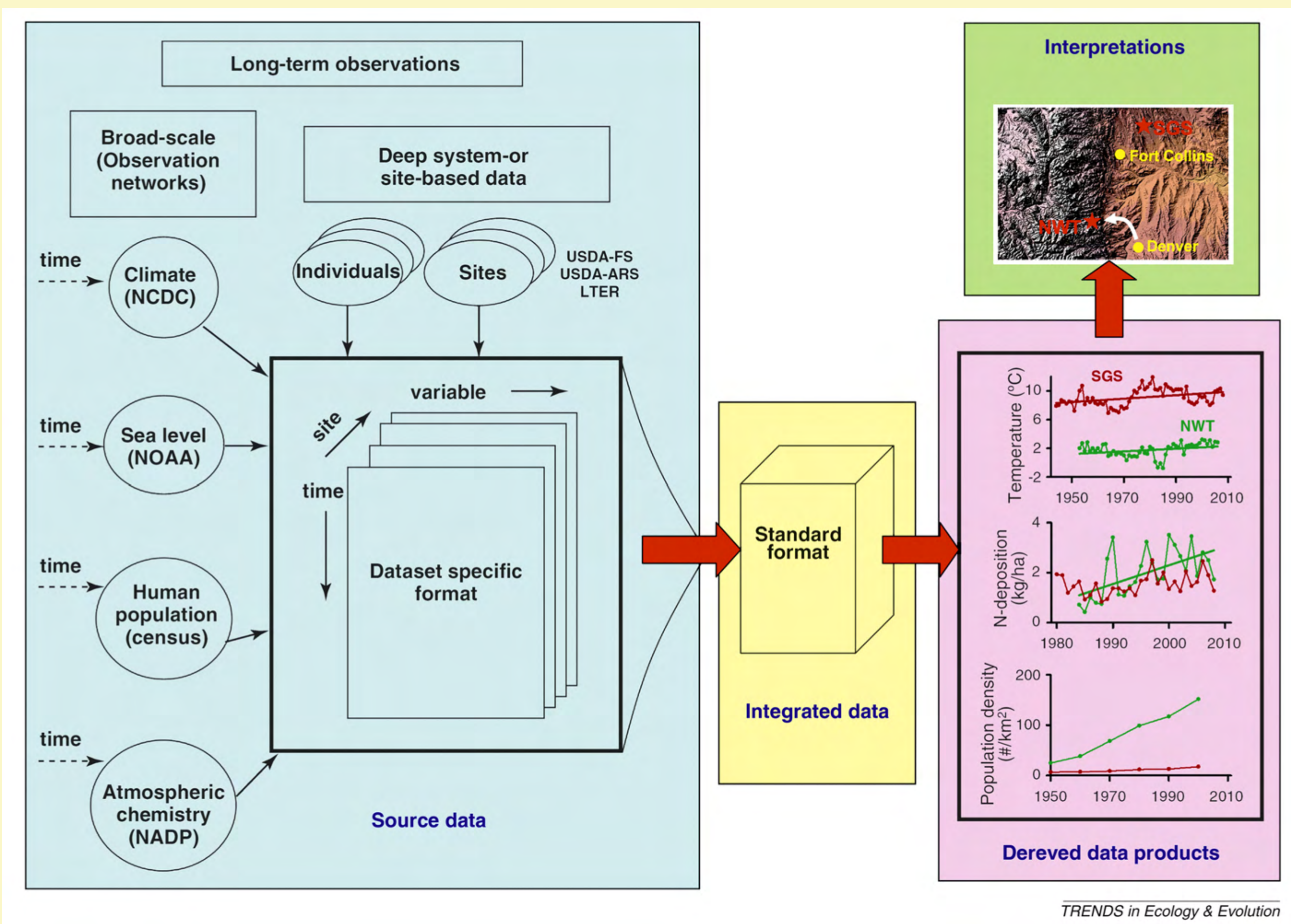

Figure I. Data from the EcoTrends Project (http://www.ecotrends.info) illustrate the first four steps of a developing framework for synthesis.

agencies) working as organized groups within structured (e.g. synthesis centers: NCEAS, NESCent, NIMBioS, and Powell Center) and unstructured environments (e.g. crowdsourcing [71]) are needed as well as other knowledge sources, such as citizen science initiatives (e.g. NPN; and North American Breeding Bird Survey, http://www.pwrc.usgs.gov/BBS/), and Traditional Ecological Knowledge [72]). A combination of quantitative and qualitative approaches and software development will be needed to blend diverse data, concepts, and theories from many disciplines. Training in using these new approaches will also be needed. These interpretations need to provide important feedbacks to data collection and software development activities.

Fifth, these new interpretations need to inform policies, practices, and actions, and can be used directly to guide decision-making by individuals as well as by local, state, and federal policymakers (Box 1). In some cases, making data easily accessible and synthesized into best knowledge at the time may be insufficient to guide policy given other constraints (e.g. Kyoto Protocol and Copenhagen Accord: http://unfccc.int/). These applications, whether put into play or not, also need to provide feedbacks to data collection activities.

Applying the framework

The utility of this framework is illustrated by recent analyses from the EcoTrends Project (http://www.ecotrends.info). The aim of this project is to integrate and make easily accessible long-term data from many sources in four major categories: climate and climate-related drivers; air and stream water chemistry; human populations; and plants and animals [19]. At present, 50 US funded sites are included that represent ecosystems found globally (forests, grasslands, deserts, arctic, alpine, lakes, streams, coastal, urban). Here, key elements of the synthesis framework (Box 2) are used to show how *post hoc* comparisons of long-term data can be used to address the following scientific questions: How does continental- and regional-scale variation compare for trends in multiple drivers? What is the explanation for regional variation in drivers? What are the potential consequences of future changes in these drivers?

The continental US was selected as the broad-scale spatial unit, and the Rocky Mountains and eastern plains of Colorado were selected as the region for trends in four drivers: climate (precipitation and temperature), nitrogen deposition, and human population density. First, long-term source data for each driver were assembled from observation networks, research sites, and individuals. Second, data were tested and verified for completeness and accuracy, and then integrated into a standardized database. Third, derived data products were created by aggregating data into a common temporal unit (annual); the spatial unit was a site. Daily precipitation and event-based nitrogen deposition were summed for each year, and average daily temperature was averaged for each year. Human population density data on a decadal scale required no aggregation. The aggregated data were graphed through time for each site, and the trend based on the slope of a simple linear regression was calculated for each variable through time.

These comparable data were then used to answer our first question: high spatial variation in trends in air temperature and precipitation across the continent (not shown) does not necessarily reflect regional patterns [19,58]. Nitrogen emissions and deposition are higher on-average in the west compared to the east [19,73,74]. Human population density is increasing throughout the country, although rates over the past 50 years have been highest in the southwest and along the coasts [4,19,65]. Patterns are also highly variable within a region (Box 2). For example, temperature and population density are increasing, although at different rates for two sites in Colorado. Precipitation is not changing at either site (not shown), and nitrogen deposition is either increasing or not changing. These results can be used to guide decisions about air pollution mitigation for the increase in nitrogen in the mountains [75], and about global warming given the increase in temperature at both sites [2].

To answer our second question about explanations for this variability requires additional information in the fourth step. Specifically, information is needed about atmospheric sources of nitrogen and circulation patterns that affect nitrogen deposition (Box 2). Our third question about future consequences to ecological systems requires information, such as biotic sensitivity to nitrogen, and a synthesis of understanding about processes driving past patterns, how the drivers and ecosystems are changing, and how the past and present dynamics of ecosystems are likely to influence their future [79,80].

Prospects

Scientists have a responsibility to make their data accessible to others, where accessibility goes beyond making complex source data and metadata available on-line. The need for an understanding of scientific data by the public and decision-makers is critical if solutions to environmental problems are to find general acceptance [6,12,13]. A synthesis framework to integrate large volumes of complex data, often collected over long time periods, into coherent, easy-to-understand formats with other sources of knowledge shows great promise to link scientists with the rest of the world and to meet the challenges required by environmental problems. The framework allows general users to understand how drivers and responses are changing, and to critically examine the consequences of these changes and their personal actions to future dynamics of ecological systems.

Ecological knowledge obtained from traditional strategies (long-term studies; short-term process-based studies; and broad-scale observations) as well as non-traditional sources, such as citizen science initiatives and crowdsourcing, is invaluable to improved understanding and prediction through synthesis. These knowledge sources need to be integrated in novel, coherent ways to promote synthesis [10], and to strategically determine additional data needs [19]. More scientists need to be trained in quantitative synthesis, visualization and other software tools; assessments are limited more by there being few scientists trained in synthesis and communication than by deep knowledge of system dynamics [8,11]. The recent emergence of observation networks to capture variability across regions, continents, and oceans is important [16,61–64], but linking these networks with established sites and research programs for long-term context and deep understanding [42–49] is critical to optimizing resources with research needs.

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