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Long-Term Trends in Ecological Systems:

A Basis for Understanding Responses to Global Change

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Long-Term Research Across Sites, Ecosystems, and Disciplines: Synthesis and Research Needs

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Dramatic changes in climate, land cover, and habitat availability over the past several centuries influence nearly every ecosystem on Earth (MEA 2005, IPCC 2007). Large amounts of data have been collected to document these changes, such as shifts in species dominance, loss of biodiversity, and reductions in clean air and water (Parmesan and Yohe 2003, Grimm et al. 2008b). Solutions to these environmental problems have been more elusive because much of the data remain inaccessible to a broad audience (Bennett et al. 2005, SNE 2008). Most data are too technical or complicated for general use, and many data are posted online in nonstandard formats. Inaccuracies in the data and missing descriptive metadata further limit accessibility (chapter 16). Some complex data have been distilled into useful formats for nonscientists (MEA 2005, SNE 2008), but questions can arise as to how the data were interpreted or analyzed.

The EcoTrends Project is one of the first attempts to standardize, simplify, integrate, and visualize data from diverse terrestrial, aquatic, and marine ecosystems in order to promote understanding and synthesis by a broad audience. This chapter discusses key scientific results from this project, describes developing conceptual and operational frameworks for cross-site synthesis, and provides recommendations for future research.

What Have We Learned Scientifically?

Long-term ecological research started over a century ago in the United States to address public concern for the future of the Nation's resources and with a belief that historic information would be important to future generations. Specific sites and individuals dedicated to data collection required a long-term vision to sustain their efforts through the characteristic turmoil of turnover in personnel, land ownership, funding agencies, and government policy. Fortunately, the development of networks of sites over the past century, either by Federal agencies like USDA Forest Service (FS) and USDA Agricultural Research Service (ARS) or by programs such as the Long Term Ecological Research Program (LTER) funded by the National Science Foundation, provided a broader scale vision with some coherence in data collection and standardization.

The data assembled in this book are a testament to this continuing dedication by individuals, sites, networks, and funding agencies. The data, graphs, and maps also provide a strong statement about the importance of continued collection of ecological data as environmental drivers continue to change, with consequences for both natural and human-dominated systems. Key results are described below for patterns in environmental drivers and in response variables.

Patterns in Environmental Drivers. Even though most data in this book were not collected to address cross-site ecological questions, comparisons of long-term data across sites illustrate regional- and continental-scale patterns in environmental drivers. Mean air temperature has increased at 24 of our 50 sites, and annual precipitation has increased at 9 sites with no obvious spatial distribution in either climate variable (figure 11-3). Changing climatic patterns are affecting both terrestrial and marine ecosystems (chapter 3).

Trends in atmospheric chemistry show clear patterns across the continent, with reduced deposition of nitrate and sulfate in precipitation through time in the Eastern States as compared with the West (figures 12-1 and 12-22). These patterns in deposition reflect Federal policies that had different effects geographically because of different sources of chemical inputs to the atmosphere (chapter 6). Increases in nitrogen have increased primary production globally and decreased biodiversity in many herbaceous communities (chapter 7).

Patterns in stream-water chemistry across sites do not reflect broad-scale patterns in atmospheric chemistry (figures 12-19 thru 12-21 and 12-30 thru 12-34); thus, local conditions (for example, soils, geology, topography, vegetation, adjacency to urban areas) strongly influence chemical inputs to and losses from streams. Patterns in disturbance events and ecosystem responses are more difficult to compare across sites (chapter 9), although recent conceptual advances should promote cross-site comparisons in the future (Peters et al. 2011).

Human population density has increased at all sites, although at different rates (figure 13-1). The Eastern States are more heavily populated than those in the West (figure 8-1), although parts of the West, such as Phoenix, AZ, have experienced some of the highest rates of increase over the past 50 years (chapter 13). This urbanization can have large impacts locally within urban ecosystems (Grimm et al. 2008a), in natural ecosystems at large distances from cities (Grimm et al. 2008b), and globally through long-distance environmental teleconnections (Adger et al. 2009). Disturbance regimes associated with climate, pollution, and human activities are also changing at many sites, resulting in significant effects on ecosystems (chapter 9).

Integrating multiple sources of long-term data provides new insights into both temporal and spatial dimensions of ecological systems. Long-term data have shown that space-for-time substitutions commonly used in ecology are not always appropriate and may result in misleading conclusions (figure 5-6). Combining site-based data through time on ecological processes with climatic data collected by the National Weather Service since the late 1800s, atmospheric chemistry data from the National Atmospheric Deposition Program since the 1970s, and human population and economy data from the U.S. Census Bureau since the late 1700s provides the temporal context for understanding trends in ecological responses. For example, sea level is increasing at all nine coastal sites (figure 11-13), with important effects on ecosystem processes and services (Hopkinson et al. 2008). In general, these sites also have high population densities and became urban areas earlier than inland sites (figure 13-2). In addition, mean air temperature is increasing at six of these sites (figure 11-3), and water temperature is increasing at two coastal sites in California (figure 11-19). Thus, multiple drivers, each with a different magnitude, timing, and rate of change, are interacting to influence these coastal ecosystems through time.

Placing site-based dynamics within a broader spatial context of landscape-, regional-, continental-, and global-scale patterns in drivers shows connectivity in the flow of material and information among different systems or nonadjacent locations (Peters et al. 2008). At the landscape scale, spatial heterogeneity in aboveground net primary production (ANPP; figures 14-1 through 14-3) can be related to within-site variation in redistribution of water from upslope to downslope topographic positions (Peters et al. 2006) and in the disturbance regime (Briggs and Knapp 1995). At broader scales, regional patterns in precipitation chemistry can reflect rainfall patterns that connect cities (as sources of nitrate and sulfate) more closely to upslope mountainous areas rather than to nearby agricultural land (figure 6-4).

Patterns in Ecological Responses. Although a large number of biological response variables are collected, measured, or sampled on plants, animals, and microbes at every site included in this project, relatively few (six) biotic variables met our criteria for inclusion in this book (more than 10 years of data, collected from a number of sites, data and metadata in a form suitable for synthesis). Time constraints and resource limitations resulted in many datasets being left out of these initial analyses. However, the plant and animal datasets that are included provide useful information for cross-site comparisons. All LTER sites collect primary production or plant biomass data that can be compared across diverse terrestrial, aquatic, and marine systems (figures 14-1 thru 14-6) similarly to how terrestrial systems have been analyzed (chapter 5). Many of the USFS and ARS sites also collect similar data. A subset of sites also collect plant and animal richness data and animal abundance data, with insects and mammals providing the most comparable datasets across the most sites (figures 14-7 thru 14-12). Biotic data are often idiosyncratic in that they reflect high spatial and temporal variability inherent in biological phenomena; thus cross-site comparisons after the data have been collected are challenging, and in many cases it is not possible to convert these data to common metrics for comparison.

Conceptual Framework for Synthesis

Assembling long-term data across a diverse set of sites allows us to draw generalizations, primarily about patterns and trends in individual environmental drivers or key response variables that either have been collected using standard methods or can be converted to similar units (chapters 11-14). These a posteriori comparisons of patterns within and among individual datasets are extremely valuable as a first step in developing a framework for synthesis across sites. However, these comparisons are insufficient to address many questions. A conceptual framework for cross-site synthesis is being developed that integrates three strategies associated with ecological research: pattern-process studies for deep understanding within a site, long-term studies, and broad-scale patterns from observation networks of sites (Peters 2010).

Ecology of the "deep." Many sites collect a wealth of information in great detail about processes and about pattern and process relationships (chapters 3-10) that go beyond comparisons of pattern alone (chapters 11-14). This drilling down into the complex interactions that make up an ecological system are needed as part of a synthesis framework in order to understand and predict dynamics at a site representative of an ecosystem type (Peters 2010). This information integrates system components vertically, both literally in that aboveground and belowground structural components are integrated and also figuratively in that hierarchical levels of organization are integrated (for example, genes, individuals, populations, species, communities, and ecosystems) as well as pattern-process relationships across spatial and temporal scales (Levin 1992, Carpenter and Turner 2000, Turner 2005). Predicting future dynamics of ecological systems requires detailed understanding and integration of the interactions and feedbacks among many components (examples are found in Driscoll et al. 2001, Hobbie et al. 2003, Seastedt et al. 2004, Briggs et al. 2005, Ducklow et al. 2007).

Ecology of the "long." Observations collected through time for many sampling periods are needed to determine the rate and direction of change, to distinguish long-term trends from short-term variability, and to assess the importance of infrequent events as well as time lags in responses (Magnuson 1990, Kratz et al. 2003, Likens 2004, Lugo 2008). The ecology of the long was suggested as a complement to process-based studies conducted over short time periods at a site (Carpenter 2002). Long-term data from diverse sites can be used in a qualitative way to investigate similarities in processes across sites. These similarities can then be used to develop or modify general ecological theories. For example, shifts from one state of a system to another state show similar patterns through time for many systems: Abundance of one dominant species decreases through time as the abundance of another species increases until there is a shift in dominance (chapter 4). These shifts in dominance (state changes) are often driven, at least in part, by climate but are reinforced by internal (among the biota) feedbacks that make reversals to the previous state very difficult (Carpenter 2003). Comparisons of two very different systems (desert plants and Antarctic penguins) show that these internal feedbacks can have strong similarities. In the Western Antarctic Peninsula (WAP), a shift back to a climate favorable to Adélie penguins may not result in recovery of this population over ecological time scales (decades to centuries) if potential source populations remaining in higher latitudes are too fragmented to overcome the critical thresholds in recruitment and survival needed to export individuals back to the Peninsula (W.R. Fraser, personal communication).

Similarly, perennial grasses that historically dominated much of the American Southwest have been reduced to remnant populations within large areas of shrublands (figure A1-43). A change in climate that favors grasses may not result in increased recruitment and survival if seeds can not disperse beyond these isolated grass patches. Cross-site studies "by design" (chapter 10) are needed to compare processes and patterns driving dynamics in these very different systems.

Ecology of the "broad." The third component of a synthetic framework for cross-site synthesis is integrating observations collected by networks of sites designed to examine broad-scale patterns in drivers and responses (Peters 2010). Observation networks of sites collecting similar data across broad areas have been operational in the United States since the National Weather Service started collecting meteorological data in 1870 (http://www.nws.noaa.gov/). Streamflow has been monitored at some sites for over 100 years (http://waterdata.usgs.gov), and the census of human demography and economy began in the 1700s (http://www/census.gov). A number of observational networks have emerged over the past decade to collect similar ecological data using standard protocols (Peters et al. 2008), including the Ocean Observatories Initiative (Clark and Isern 2003), the WATERS Network (http://www.watersnet.org), and the National Ecological Observatory Network (Keller et al. 2008). Other networks are collections of sites with similar missions, such as the ARS network of rangeland sites and the USFS network of experimental forests. Both collect data with site-specific methods, so standardization is required before comparisons can be made (Lugo et al. 2006, Moran et al. 2008).

Operational Framework for Synthesis

As part of the EcoTrends Project, we integrated different types and sources of data from these three strategies of ecological research into one operational framework with three key steps (figure 17-1).

First, data from all three strategies were obtained from four sources:

- downloaded from standardized Internet pages containing many sites, such as climate data from the National Climate Data Center,
- downloaded from Internet pages of individual research sites or scientists,
- received directly from scientists who collected the data, and
- received from an information manager or staff personnel with access to the data.

These source data were checked for errors in values and format and then assembled into a common database structure. The quality of the data varied such that the amount of work required to obtain "clean" data also varied (chapter 16).

Then common aggregations were conducted on the source data to reduce the complexity of the structure of each dataset and to create a common format for multisite comparisons. Finally, these new data products were used to generate the graphs in this book (chapters 11-14).

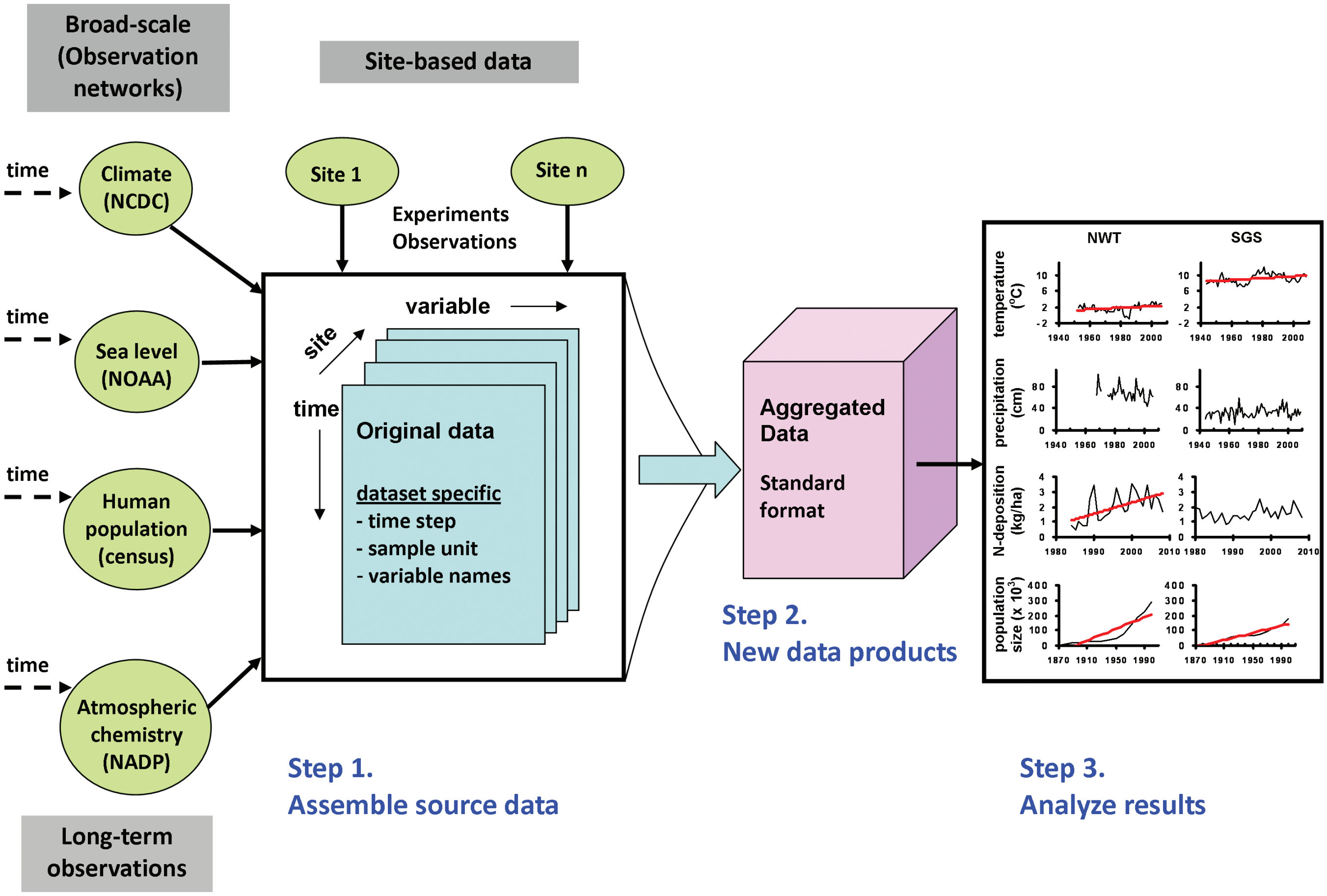


Figure 17-1. Operational framework for assembling different sources of data into a database of new products that allows and encourages cross-site comparisons and synthetic analyses. Redrawn from Peters (2010).

Recommendations: What Do We Still Need To Do?

Rather than an exhaustive list of all possible research needs for the future, a few key recommendations are noted here based on experiences from this project:

1. Conduct "by-design" cross-site, multiscale experiments of multiple drivers combined with observation networks.

    a. Conduct experiments of multiple interacting drivers operating across a range of spatial and temporal scales for diverse ecosystem types. Quantitative comparisons of processes across sites require experimental manipulations of resources or populations, such as invasive species, pests, or pathogens, within and among diverse ecosystem types. Examples of these manipulative studies exist primarily within an ecosystem type (Chapter 10), although there are notable exceptions (the Long-Term Intersite Decomposition Experiment Team; see Parton et al. 2007). Experiments are needed that integrate (1) horizontally to include patterns in multiple interacting drivers across broad spatial extents and multiple ecosystem types and (2) vertically to include depth of knowledge about changing pattern-process relationships across scales. These experiments are expected to provide insights into understanding and predicting ecological dynamics in the future.

    b. Conduct long-term experiments or monitoring of variables that are not well understood or easily standardized. These variables include many belowground components of ecological systems, such as soil respiration, belowground net primary production and biomass, and microbial diversity, abundance, and biomass. Long-term biotic datasets that could be easily standardized and compared are relatively scarce, and this scarcity severely limited useful cross-site comparisons of ecological responses to environmental drivers. In addition, many datasets are not of sufficient duration for determining trends. In many cases, biotic datasets have been collected but are missing metadata, limiting their usefulness to others.

    c. Conduct long-term experiments to allow comparisons of disturbances and experimental manipulations across sites. Although disturbance regimes and ecological responses to disturbance are studied at most sites, these data are not collected or structured in a standardized way that allows comparisons. Progress has been made in defining disturbances by events rather than by types and in decomposing an event into its constituent drivers and responses (Peters et al. 2011). Similar procedures are needed for experimental manipulations.

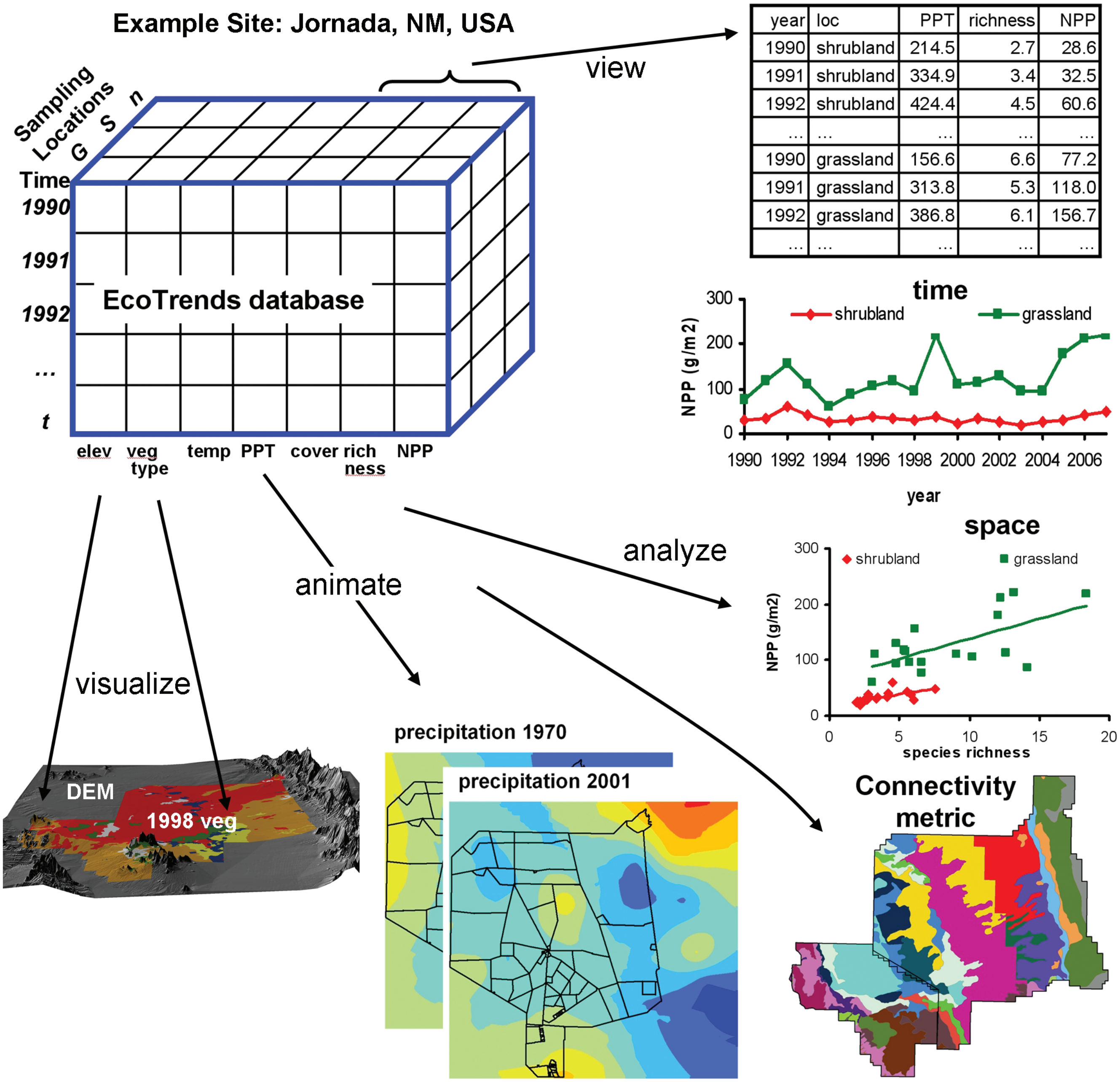
2. Expand the scope of the project (sites, within-site sampling locations, variables, web-based tools) (figure 17-2).

    a. Add sites to improve representation of the ecosystems of the United States and the World. Large areas of the Western United States are not represented, in particular the cold deserts of the Great Basin and Colorado Plateau, Mediterranean shrublands, and annual grasslands of California; in addition, greater representation of the central Great Plains grasslands is warranted. Freshwater systems are not included, and the one site that focuses on lakes (North Temperate Lakes, NTL) was classified here as eastern forest to allow cross-site comparisons. Diverse systems in large states, such as Alaska (currently two sites) and Texas (one site), should be represented. In addition, more urban sites (two sites) should be added as well as sites that examine interfaces, such as urban-natural systems, land-water margins, and elevational gradients.

    b. Add locations to characterize spatial variability within a site. For most variables, our initial analysis included one sample location selected by a site investigator to represent that site. High spatial variability in drivers and responses across many sites cannot be studied without additional sample locations. Connectivity in transfer processes that may include dynamics, such as wind and water erosion-deposition patterns, also cannot be examined without more locations.

c. Add variables that did not meet our initial criteria. Additional variables that are specific to a few sites, with shorter records than 10 years, or have complicated data structures should be added to improve understanding and prediction. Contextual variables, such as soil texture, landform, and topographic information (elevation, slope, aspect), that may not change through time should also be added.

d. Add tools to the web-based user interface that will enable users to fully understand the data, and to enable within- and among-site comparisons. Tools for visualizing, animating, and analyzing the data statistically will allow users to more easily see trends in time and through space.



year	loc	PPT	richness	NPP
1990	shrubland	214.5	2.7	28.6
1991	shrubland	334.9	3.4	32.5
1992	shrubland	424.4	4.5	60.6
...	...	...	...	...
1990	grassland	156.6	6.6	77.2
1991	grassland	313.8	5.3	118.0
1992	grassland	386.8	6.1	156.7
...	...	...	...	...

Figure 17-2. Web-based tools that allow visualization, animation, and analysis of derived data products are needed to fully utilize long-term data from many sites to address critical questions from a broad audience.

Summary Recommendation: Make Data and Associated Metadata Easily Accessible to and Usable by Others.

This is the strongest recommendation that follows logically from this project. Many thousands of datasets have already been collected; analyses in this book and on the current website (http://www.ecotrends.info) represent an important initial step in bringing a small subset of these datasets together for comparisons across sites. However, merely collecting more data from more experiments, sampling locations, and sites will not achieve the level of synthesis recently identified as critical to advancing science (Carpenter et al. 2009).

In addition, the commonly used approach of providing large amounts of source data and metadata on Internet sites does not meet policies of U.S. Federal agencies, which state that data must be released to the general public in a timely manner. Source data and metadata on Internet sites are often inaccessible to general users because of the complicated sampling designs, terminology, and formats used by scientists. In addition, data are often posted without quality assurance and quality control, common formats and metrics, and aggregation procedures needed to understand and use the data. In some cases, data and metadata have serious shortcomings that need to be addressed prior to posting (chapter 16). In other cases, data accessibility can be improved by developing Internet pages that promote data access and use by a general audience beyond scientists and technical experts (Peters 2010).

Our approach to improving data accessibility is to provide logical aggregations of the original data that can be easily used to compare sites or datasets. One example of aggregation to a new data product is to convert seasonal biomass data collected from many quadrats in a complicated sampling design to an annual net primary production value for that site. We also provide either the source data or links to that data for users interested in that level of detail.

Thus, we strongly recommend a three-pronged approach:

- Provide quality assurance and control on existing and historic datasets.
- Collect more data through experiments and observations that promote cross-site, cross-system comparisons, both within the United States and internationally.
- Make all of the data and metadata easily accessible and usable by others.

Without this approach, we will remain limited in the application of these research sites and datasets for the conservation of our Nation's resources.

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