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A Basis for Understanding Responses to Global Change

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Long-Term Trends in Ecological Systems:

A Basis for Understanding Responses to Global Change

Debra P.C. Peters, Christine M. Laney, Ariel E. Lugo, Scott L. Collins, Charles T. Driscoll, Peter M. Groffman, J. Morgan Grove, Alan K. Knapp, Timothy K. Kratz, Mark D. Ohman, Robert B. Waide, and Jin Yao

Abstract

Peters, D.P.C., C.M. Laney, A.E. Lugo, et al. 2013. Long-Term Trends in Ecological Systems: A Basis for Understanding Responses to Global Change. U.S. Department of Agriculture, Technical Bulletin Number 1931.

The EcoTrends Editorial Committee sorted through vast amounts of historical and ongoing data from 50 ecological sites in the continental United States including Alaska, several islands, and Antarctica to present in a logical format the variables commonly collected. This report presents a subset of data and variables from these sites and illustrates through detailed examples the value of comparing long-term data from different ecosystem types. This work provides cross-site comparisons of ecological responses to global change drivers, as well as long-term trends in global change drivers and responses at site and continental scales. Site descriptions and detailed data also are provided in the appendix section.

Keywords: atmospheric chemistry, climate change, cross-site comparisons, disturbance, ecology, ecological response, ecosystem, EcoTrends, experimental forests, global change, human demography, human population growth, long-term datasets, Long Term Ecological Research (LTER), precipitation, rangeland, rangeland research stations, surface water chemistry.

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While supplies last, single copies of this publication can be obtained at no cost from Debra Peters, USDA-ARS Jornada Experimental Range, Box 30003, MSC 3JER, NMSU, Las Cruces, NM 88003-0003 or by e-mail at debpeter@nmsu.edu.

Copies of this publication may be purchased in various formats (microfiche, photocopy, CD, print on demand) from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, (800) 553-6847, www.ntis.gov.

This publication in its entirety also is freely accessible on the Internet at http://www.ars.usda.gov/is/np/indexpubs.html.

September 2013

Preface

Long-term ecological research within the United States dates back to 1902, when areas were set aside as research centers. By 1980, when the Long Term Ecological Research (LTER) program was established, 78 experimental forests and more than 10 rangeland research stations had been conducting research, in most cases for more than 40 years. This suite of sites supported by the National Science Foundation (NSF) and the U.S. Department of Agriculture (USDA), including 26 LTER sites, represents a wide range of ecosystem types, including forests, grasslands and shrublands, and freshwater lakes and streams, near coastal marine areas and estuaries, urban areas, and arctic, alpine, and antarctic systems.

A variety of different kinds of data have been collected from these sites through time, ranging from primarily climatic and human demographic data since the 1800s to more recent quantitative monitoring of plant, animal, and microbial populations and communities, hydrological and biogeochemical cycles, biodiversity, and disturbance regimes. However, for the most part, these data have not been easily accessible to others. The EcoTrends project began in 2004, when two scientists (D. Peters and A. Lugo) saw a need to synthesize and make easily accessible long-term datasets in order to compare continental-scale and national-level trends in ecological responses to changing environmental drivers.

Because Peters (USDA Agricultural Research Service) and Lugo (USDA Forest Service) are employed by different USDA agencies with existing networks of sites and are actively involved in the LTER program, the EcoTrends project began as a multiagency collaboration. As the complexity of the project became clearer in terms of the number and types of long-term datasets available (climate, atmospheric deposition and fertilization, natural disturbance, and human activities), a group of experts were convened to make decisions about these diverse data types from many ecosystem types. This active and productive group of experts, the EcoTrends Editorial Committee (the authors of this book), sorted through the vast amounts of historical and ongoing data from all 50 sites to select and present in a logical format and organization the variables commonly collected.

Considerable time and effort was invested by scientists, information managers, and technical staff at every site to locate the data, verify data quality and quantity, and provide the data and metadata in standard formats. A group of technical consultants assisted in data standardization and accessibility issues needed for website development and for use by a broad community.

Two products resulted from these activities: a book and an initial website (http://www.ecotrends.info), where data contained in the book and their metadata are accessible for discovery, visualization, download, and analysis. This book and the website would not have been possible without these combined efforts.

The goals of the EcoTrends Project include—

- Provide a platform for synthesis by making long-term data more readily accessible.
- Illustrate the application of this platform in addressing within-site and network-level scientific questions.
- Demonstrate the importance of collaborative activities among State universities and multiple Federal agencies.

This book and the associated website contain a small subset of data and variables from 50 ecological sites in the United States. More variables, datasets, and sites will be needed in the future to meet our goals.

A large number of people and agencies made this book possible, including students, faculty, and researchers working alone or together to collect data over time. Institutional support for data archiving and standardization of methods and metadata allowed this project to be successful. Credit is given to each investigator when appropriate. In a project of this magnitude, it is impossible to provide appropriate recognition to

the hundreds of individuals who have contributed to the final product. We apologize in advance for any inadvertent omissions.

The authors thank the USDA-ARS Jornada Experimental Range for continued logistical, hardware, software, and personnel support. The authors also thank the following: the National Science Foundation for support to New Mexico State University (DEB 0618210) for project management, coordination, and personnel; the University of New Mexico (DEB 0832652) for website development; the LTER sites for providing data and metadata; USDA Agricultural Research Service and USDA Forest Service for providing personnel, time, and resources for collecting and making available series of data covering very long periods; and the scientists and information managers at each site for their time and effort in providing data, metadata, and illustrations for this massive project.

Contents

Contributors

Karen S. Baker
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093
kbaker@ucsd.edu

John M. Blair
Division of Biology
Kansas State University
Manhattan, KS 66506
jblair@ksu.edu

Christopher G. Boone
School of Sustainability
Arizona State University
Tempe, AZ 85287
cgboone@asu.edu

Joel R. Brown
Jornada Experimental Range
USDA/Natural Resources Conservation Service
Las Cruces, NM 88003
joelbrow@nmsu.edu

F. S. Chapin III
Department of Biology and Wildlife
University of Alaska
Fairbanks, AK 99775
fschapiniii@alaska.edu

Christopher M. Clark
EPA/National Center for Environmental Assessment
Washington, DC 20460
chris.michael.clark@gmail.com

Scott L. Collins
Department of Biology
University of New Mexico
Albuquerque, NM 87131
scollins@sevilleta.unm.edu

Charles T. Driscoll
Department of Civil and Environmental Engineering
Syracuse University
Syracuse, NY 13244
ctdrisco@syr.edu

William R. Fraser
Polar Oceans Research Group
Sheridan, MT 59749
bfraser@3rivers.net

Ted L. Gragson
Department of Anthropology
University of Georgia
Athens, GA 30602
tgragson@uga.edu

Peter M. Groffman
Cary Institute of Ecosystem Studies
Millbrook, NY 12545
groffmanp@caryinstitute.org

J. Morgan Grove
USDA/Forest Service
South Burlington, VT 05403
jmgrove@gmail.com

Kris M. Havstad
Jornada Experimental Range
USDA/Agricultural Research Service
Las Cruces, NM 88003
khavstad@nmsu.edu

Sally J. Holbrook
Department of Ecology, Evolution, and Marine Biology
University of California, Santa Barbara
Santa Barbara, CA 93106
holbrook@lifesci.ucsb.edu

Alan K. Knapp
Department of Biology
Colorado State University
Fort Collins, CO 80523
Alan.Knapp@ColoState.edu

Timothy K. Kratz
Trout Lake Station
University of Wisconsin-Madison
Boulder Junction, WI 54512
tkkratz@wisc.edu

Christine M. Laney
Jornada Experimental Range
New Mexico State University
Las Cruces, NM 88003
christine.laney@gmail.com

Ariel E. Lugo
Jardin Botanico Sur
USDA/Forest Service
Río Piedras, PR 00926
alugo@fs.fed.us

Mark D. Ohman
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093
mohman@ucsd.edu

Debra P.C. Peters
Jornada Experimental Range
USDA/Agricultural Research Service
Las Cruces, NM 88003
debpeter@nmsu.edu

Kenneth W. Ramsey, Jr.
Department of Biology
New Mexico State University
Las Cruces, NM 88003
kramsey@jornada.nmsu.edu

Andrew Rassweiler
Department of Ecology, Evolution, and Marine Biology
University of California, Santa Barbara
Santa Barbara, CA 93106
rassweil@lifesci.ucsb.edu

Osvaldo Sala
School of Life Sciences and School of Sustainability
Arizona State University
Tempe, AZ 85281
osvaldo.sala@asu.edu

Russell J. Schmitt
Department of Ecology, Evolution, and Marine Biology
University of California, Santa Barbara
Santa Barbara, CA 93106
schmitt@lifesci.ucsb.edu

Melinda D. Smith
Department of Biology
Colorado State University
Fort Collins, CO 80526
melinda.smith@colostate.edu

Katharine N. Suding
Department of Environmental Science, Policy, and Management
University California, Berkeley
Berkeley, CA 94720
suding@berkeley.edu

Frederick J. Swanson
Pacific Northwest Research Station
USDA/ Forest Service
Corvallis, OR 97331
fred.swanson@oregonstate.edu

Alan J. Tepley
Department of Geosciences
Oregon State University
Corvallis, OR 97331
tepleya@science.oregonstate.edu

Robert B. Waide
LTER Network Office
University of New Mexico
Albuquerque, NM 87131
rwaide@lternet.edu

Jin Yao
Jornada Experimental Range
New Mexico State University
Las Cruces, NM 88003-0003
jyao@nmsu.edu

Technical Consultants

James Brunt
LTER Network Office
University of New Mexico
Albuquerque, NM 87131
jbrunt@lternet.edu

Duane Costa
LTER Network Office
University of New Mexico
Albuquerque, NM 87131
dcosta@lternet.edu

Charlene d'Avanzo
School of Natural Science
Hampshire College
Amherst, MA 01002
cdavanzo@hampshire.edu

Donald Henshaw
Pacific Northwest Research Station
USDA/ Forest Service
Corvallis, OR 97331
dhenshaw@fs.fed.us

Inigo San Gil
LTER Network Office
University of New Mexico
Albuquerque, NM 87131
isangil@lternet.edu

Kenneth W. Ramsey, Jr.
Department of Biology
New Mexico State University
Las Cruces, NM 88003
kramsey@jornada.nmsu.edu

Mark Schildhauer
National Center for Ecological Analysis
and Synthesis
Santa Barbara, CA 93202
schild@nceas.ucsb.edu

Mark Servilla
LTER Network Office
University of New Mexico
Albuquerque, NM 87131
mservilla@lternet.edu

Wade Sheldon
Department of Marine Sciences
University of Georgia
Athens, GA 30602
sheldon@uga.edu

Marshall White
LTER Network Office
University of New Mexico
Albuquerque, NM 87131
mwhite@lternet.edu

Chapter 1

Long-Term Trends in Ecological Systems: An Introduction to Cross-Site Comparisons and Relevance to Global Change Studies

D.P.C. Peters, C.M. Laney, A.E. Lugo, S.L. Collins, C.T. Driscoll, P.M. Groffman, J.M. Grove, A.K. Knapp, T.K. Kratz, M.D. Ohman, R.B. Waide, and J. Yao

Earth's environment is changing in many ways at local, regional, and global scales. Dramatic changes in climate, land cover, and habitat availability have occurred over the past several centuries. Long-term data (exceeding 10 years) are needed to assess the rate and direction of change, to distinguish directional trends in these changes (such as persistent increases or decreases) from short-term variability (of multiyear cycles, for instance), and to forecast environmental conditions in the future. As an indication of global changes, for example, carbon dioxide in Earth's atmosphere has been increasing since 1958 at Mauna Loa in Hawaii (Keeling et al. 2001, 2005). Although this "Keeling Curve" fluctuates from year to year, global atmospheric concentrations of carbon dioxide (CO_2) are clearly rising (figure 1-1) (Keeling et al. 2001, 2005). This global increase in CO_2 is likely responsible for the observed rise in global average temperatures and

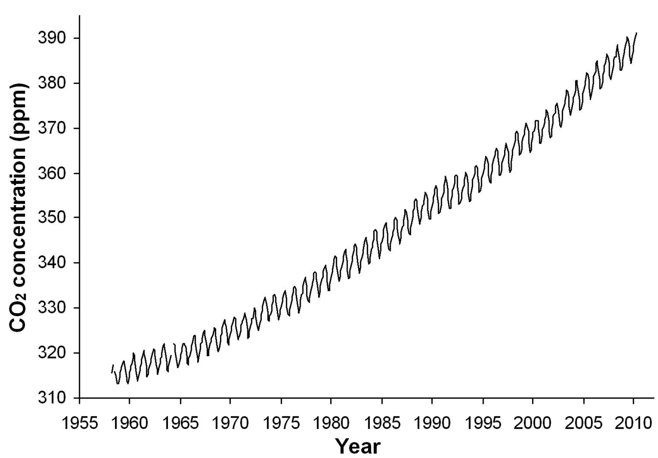

Figure 1-1. Monthly average atmospheric carbon dioxide concentration (CO_2 in parts per million in the mole fraction) through time at Mauna Loa Observatory, Hawaii (19.5°N, 155.6°W) (Keeling et al. 2001, 2005). (Data from http://scrippsco2.ucsd.edu/data/atmospheric_co2.html.)

acidification of the ocean, which lead to coral bleaching and loss of coral reefs (IPCC 2007). The spread of invasive species and of infectious diseases constitutes additional drivers of global change that have significant ecological and economic consequences. Finally, human populations are increasing in numbers, changing in economic status, and moving around the country, resulting in uneven spatial distribution of ecological impacts (Grimm et al. 2008a, 2008b).

Only by using long-term data can these changes and their effects be detected and monitored. These changes have important consequences for the services that ecological systems provide to humans, such as clean air and water and food, fiber, and energy (Daily 1997, Palmer et al. 2004, 2005). Thus, long-term data are vital for assessing status and trends of a variety of components of ecological systems and for predicting and managing future environmental conditions needed for a sustainable Earth (Magnuson 1990, Moran et al. 2008, Janzen 2009).

Fortunately, ecological research in the United States has a long history, dating from the 1800s. Sites were initially established by United States Department of Agriculture (USDA), Forest Service (FS) to preserve forests in the face of widespread fires and increasing human population density. Rangeland sites as part of USDA, Agricultural Research Service (ARS) were established to limit land degradation from overgrazing by livestock, particularly during periods of severe drought. In many cases, the initial research was observation based and focused on vegetation properties, such as plant cover.

Through time, a systems approach has become prevalent among ecologists such that many components of a system are studied, including soil properties and plant, animal, and microbial populations and communities, as well as nutrient cycling (Golley 1993). Linking ecological responses with environmental drivers was made possible initially with the National Weather Service's network of sites, which started collecting meteorological data in 1870 (http://www.nws.noaa.gov/), and more recently with site-based weather stations that are part of a large network of sites in the United States (http://www.ncdc.noaa.gov) and globally (http://www.wmo.int). Other drivers include streamflow, which has been monitored at some sites for over 100 years by the U.S. Geological Survey (http://waterdata.usgs.gov), and the census of human demography and economy by the U.S. Census Bureau since 1830 (http://www/census.gov).

With the advent of computational resources in the 1960s, long-term data collection became more practical because large quantities of information could be collected, aggregated, managed, stored, analyzed, and made accessible to others. Advances in information management and software development allowed these vast amounts and kinds of data to be accessible by current and future users (Michener and Brunt 2000). Measurement technology and coordinating activities also improved. For example, sites began monitoring precipitation chemistry in 1978 through the National Atmospheric Deposition Program (http://www.nadp.isws.illinois.edu/). As technology advanced into the 21st Century, long-term research and information systems design have become more sophisticated (Baker et al. 2000, Hobbie et al. 2003). Small, plot-based experiments have been complemented with patch- and landscape-scale extrapolations and manipulations that can be studied over long periods (Cottingham and Carpenter 1998, Carpenter 2002). Aerial photographs obtained by the U.S. Government starting in the 1930s and updated every decade have been combined since the 1970s with remotely sensed satellite images. Analyses of these images through time and space using large computational resources and new algorithms have shown fine- to broad-scale dynamics. More recent advances include wireless technology that allows data to be collected remotely and simultaneously for many locations (Porter et al. 2005, Collins et al. 2006). Theoretical, statistical, and simulation models have been developed that allow the synthesis of different sources and kinds of data for many systems, provide new insights into dynamics, guide development of new studies, and improve prediction about future dynamics for many sites and ecosystem types (for example, Parton et al. 1993, Rastetter et al. 2003).

Networks of long-term research sites and observation systems, such as the Long Term Ecological Research Network (LTER), have become increasingly important as our understanding expands about the complexities and interconnections among components of Earth as a system (Gosz 1999, Peters et al. 2008). These networks often collect similar types of data that can be used to compare sites, both within the same biome (such as multiple grassland sites) and among different biomes (for example: deserts, grasslands, and forests) (Hobbie et al. 2003). Cross-site comparisons are valuable in determining generalities in ecological responses to different drivers and in examining variation in responses to the same driver (Hobbie 2003).

However, multisite comparative studies have not reached their full potential because of limitations in our understanding of data system design and of the data themselves—their types, organization, management, and practices. In most cases, the data have been used primarily by the scientists who collected the data or their close collaborators because of issues relating to content, format, exchange, contextualization, and standards. The reasons for these data issues and resulting limitations on their use include that data—

- are collected to address site- or system-specific questions (often using site-designed methodologies),
- are recorded in unique local or proprietary formats,
- are available only directly from individual researchers or from research site web pages,
- have limited metadata, the descriptive information required to understand the sampling design and repeat the sampling methods, and
- do not include cross-references because of a lack of local or domain level vocabularies and standards.

In many cases, the data have been published either as individual studies or as part of site synthesis volumes (see http://www.oup.com/us/catalog/general/series/TheLongTermEcologicalResearchNet for an example). In cases in which synthetic papers were published to address multiple site questions (for example, Magnuson et al. 1991, Kratz et al. 1995, Riera et al. 1998, 2006; Knapp and Smith 2001, Parton et al. 2007), the data were primarily obtained directly from scientists.

The amount of data available remotely has increased with the World Wide Web; however, these data are typically in an "original" form—the way in which the data were recorded and delivered. Fully comprehending the data is often a complex undertaking because there is detailed information specific to the sampling design to consider, such as transect number, quadrat number, day of sampling, and sample number. Users often require "derived" data products that are aggregations of the originally submitted data reconfigured to allow cross-site comparisons. For example, plant production of a community can be obtained by collecting biomass samples by individual plants in a large number of small quadrats (1 m^2) located along transects designed to capture the spatial variability in a system. Total biomass of all plants (g/m^2) collected at multiple times during the year is needed to determine the change in biomass through time as an estimate of net primary production ($g/m^2/y$). It is the annual primary production of an ecosystem that is most commonly compared across sites rather than the complex original data. Precipitation provides another example of the need for derived data when comparing sites. Precipitation is collected daily, yet it is monthly or annual aggregations of precipitation that are the most useful for comparing sites.

As our ability to collect data over broad areas and long time periods increases, and our need to understand multisite dynamics increases, it will be increasingly important that these data are well documented, easy to access and use, and stored and maintained in common formats for use by future generations (chapter 16). This report and its accompanying web page (http://www.ecotrends.info) represent initial steps in the process of understanding data requirements and developing standards for long-term datasets for cross-site studies. Further, our work provides a foundation for the inclusion of additional data and sites in the dynamic online component of the project.

Purpose and Audience

The intent of this book is twofold—

- Illustrate the importance of long-term data in comparing dynamics across sites and in providing the context for understanding ecological dynamics of relevance to society (chapters 3-10), and
- Present long-term ecological data from different sources and a large number of sites in a common format that is easily understood and used by a broad audience (chapters 11-14).

The writing style, background information, and photos allow users across a range of expertise to grasp and access this information. A perusal of the figures for a specific site or region can lead to the discovery of interesting patterns, such as "Air temperature is increasing through time for a site in my area, yet precipitation is decreasing." Or "Air temperature is decreasing in my area, yet it is increasing in many other parts of the country." In this sense, the book is analogous to an amateur astronomer's telescope: It provides access to a universe of long-term data that were previously available only to a small group of scientists.

Second, the large number of detailed graphs showing long-term data for many sites serves as a key reference for students, educators, and scientists interested in detailed patterns in both global change drivers and ecosystem responses. Because these data can be downloaded from our website (http://www.ecotrends.info), more detailed analyses can be conducted by individual users.

Finally, for most of these sites, data are still being collected. This book, then, serves as an important benchmark of historical patterns that can be compared with future observations as Earth continues to change. Because data are frequently interpreted differently by different people, we present the data and trend lines with limited explanation as a prompt for users to provide their own interpretations.

Practical Applications

This book has practical applications that add to its usefulness and relevance. Land managers can use the data and figures to provide a basis for interpreting local patterns in vegetation and soils observed and managed on the ground. These patterns may be short term and can be misleading without the long-term context provided by historical data. In some cases, a short-term trend can be confirmed by long-term data, demonstrating that a change in management policy may be required. In other cases, long-term data are needed to determine whether short-term changes, such as periodic drought, are cyclic. This information can be used to justify a local, short-term management action rather than a broader scale or long-term change in policy. In addition, climate and other drivers are themselves changing and modifying these patterns in potentially unique ways. Depicting long-term trends in both drivers and ecological responses can be extremely useful for interpreting the complex patterns observed by land managers (chapter 15).

The information in this book can also help explain complex issues to the general public. There is increasing public awareness of the importance of climate change to the daily lives of people, as made popular by the movie "An Inconvenient Truth" (http://www.climatecrisis.net/). However, it is important to differentiate climate variability from a directional change in climate. For example, extremely high air temperatures in one year that kill fruit and row crops need to be differentiated from a long-term change in temperature that shifts the growing season conditions and the locations where crops can be successfully grown. Although climate change has become a favorite topic in the popular press, long-term data on temperature and precipitation at specific sites as well as the consequences of climate change to ecosystem dynamics are not readily available. This book presents a variety of data in forms that are accessible to people who are interested in distinguishing short-term variability from long-term trends in many different areas.

Scientists will find this book particularly useful for a number of reasons. In addition to being used to distinguish short-term variability from long-term trends, the information in this book can be used to identify gaps in knowledge that require new research (chapter 17). Equally important is the re-examination of results from previous research given the additional information provided by more years of data. For example, in southern New Mexico, the drought of the 1950s was often implicated in the demise of grasslands and shift to broad-scale shrub dominance associated with desertification (Buffington and Herbel 1965). Recent analyses of long-term quadrats show that grasses persist to the current day in some quadrats and were lost prior to the 1950s drought in others (Yao et al. 2006). Thus, the importance of the drought must be examined within the context of the long-term climate and vegetation record from 1915 (or earlier if possible) to the present.

Scientists can also use long-term data to help interpret results from short-term studies. Most experiments and observations in ecology are less than 5 years long; this study duration is related to the length of most research grants from State and Federal agencies in the United States (3-4 years). However, the implications of these results to ecosystem dynamics need to be extrapolated to decades or longer. Long-term data are often used in combination with simulation models as a reliable approach to making these extrapolations more meaningful. Federal agencies, such as the USDA Agricultural Research Service and Forest Service, provide a structure to support this type of long-term research that goes beyond competitive grants. The U.S. National Science Foundation through the Long Term Ecological Research Network and Long Term Research in Environmental Biology programs are also critical to the collection of long-term data by providing long-term funding (5-6 years) through competitive awards.

Site, Variable, and Data Selection

This book illustrates the value of long-term studies in two ways. First is the comparison of the dynamics of multiple sites by synthesizing published data in eight themes (chapters 3-10). Second is the comparison of data through time for four types of variables using graphs and maps (chapters 11-14). The focus is on data from 50 ecological research sites funded by U.S. agencies and located in North America and Antarctica, with one site in French Polynesia (figure 1-2, table 1-1). Twenty-six of the sites are individually funded by the National Science Foundation as part of the LTER Network (http://www.lternet.edu). Most of the remaining sites are USDA federally operated sites, either experimental forests (USFS, 14 sites) or rangelands (ARS, 7 sites); and 9 sites are affiliated with both LTER and USDA (USFS or ARS). The remaining three sites are operated by other Federal or State agencies (Loch Vale Watershed by the U.S. Geological Survey [USGS], Walker Branch Watershed by the U.S. Department of Energy, and Santa Rita Experimental Range by the University of Arizona).

These sites represent six ecosystem types common globally (arctic and alpine [including Antarctica], arid lands, coastal systems, forests, temperate grasslands and shrublands, and urban systems) (table 1-1, figure 1-3) and cover much of the range in average annual temperature and average total annual precipitation for these ecosystems (figure 1-4). The terrestrial ecosystem types broadly characterize biomes, but in many cases our ecosystem types include multiple terrestrial biomes as defined by the World Wildlife Fund (http://www.wwf.org) and others (table 1-2).

In some cases, our sites represent finer spatial resolution of ecosystem types than shown by biomes. For example, Niwot Ridge and Loch Vale are classified here as alpine sites based on the sampling location of most of their data in this book, although these locations are classified as coniferous forests based on the surrounding biome of larger spatial extent. In other cases, we generalize ecosystem types in order to simplify the presentation of data. For example, we distinguish forests, a large and diverse collection of sites, into western and eastern forests based only on their geographic location relative to the Mississippi

River. Two urban sites are distinguished in our analysis because their data collection focuses on urban effects (Baltimore Ecosystem Study and Central Arizona Phoenix); we show the biomes surrounding these cities in tables 1-1 and 1-2 to allow comparisons with similar natural ecosystems. Because coastal sites often collect data in adjoining land as well as in coastal waters, we show the land-based ecosystem type in table 1-2 to allow comparisons with similar terrestrial systems.

Variables were selected to characterize either a global change driver (climate, precipitation and stream water chemistry, human demographics) or a biotic response to drivers, primarily by plants and animals. A total of 37 variables were selected for inclusion in this book if data were available from at least 5 sites for at least 10 years and if both the original source data and the associated metadata were available (tables 1-3, 1-4, 1-5). More variables can be found on the EcoTrends website (http://www.ecotrends.info).

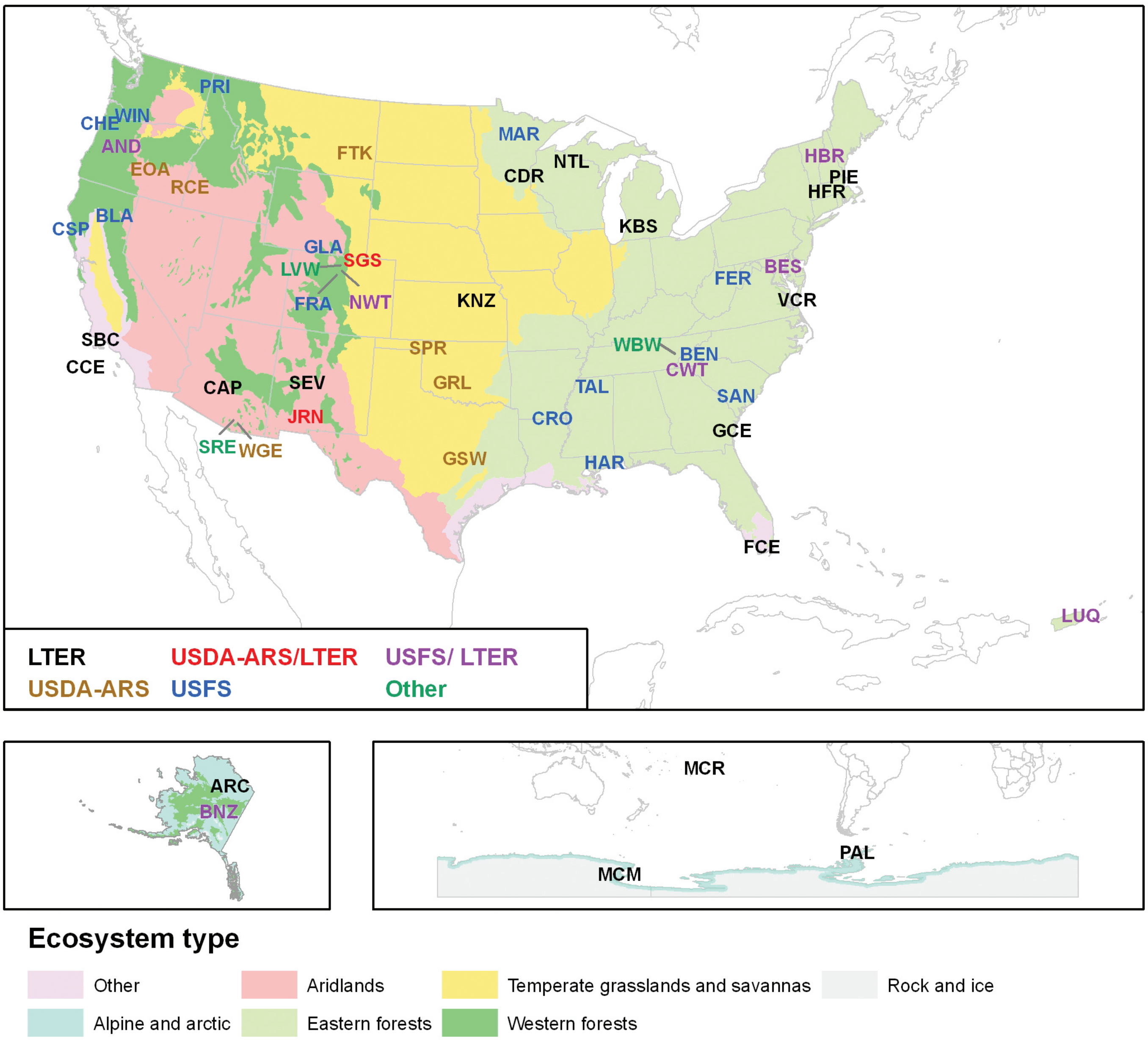

Figure 1-2. Location of sites identified by their program or funding agency, network, and agency names. Background color shows terrestrial ecosystem type used in EcoTrends from table 1-2. These colors are used throughout the book. See table 1-1 for site names and program acronyms.

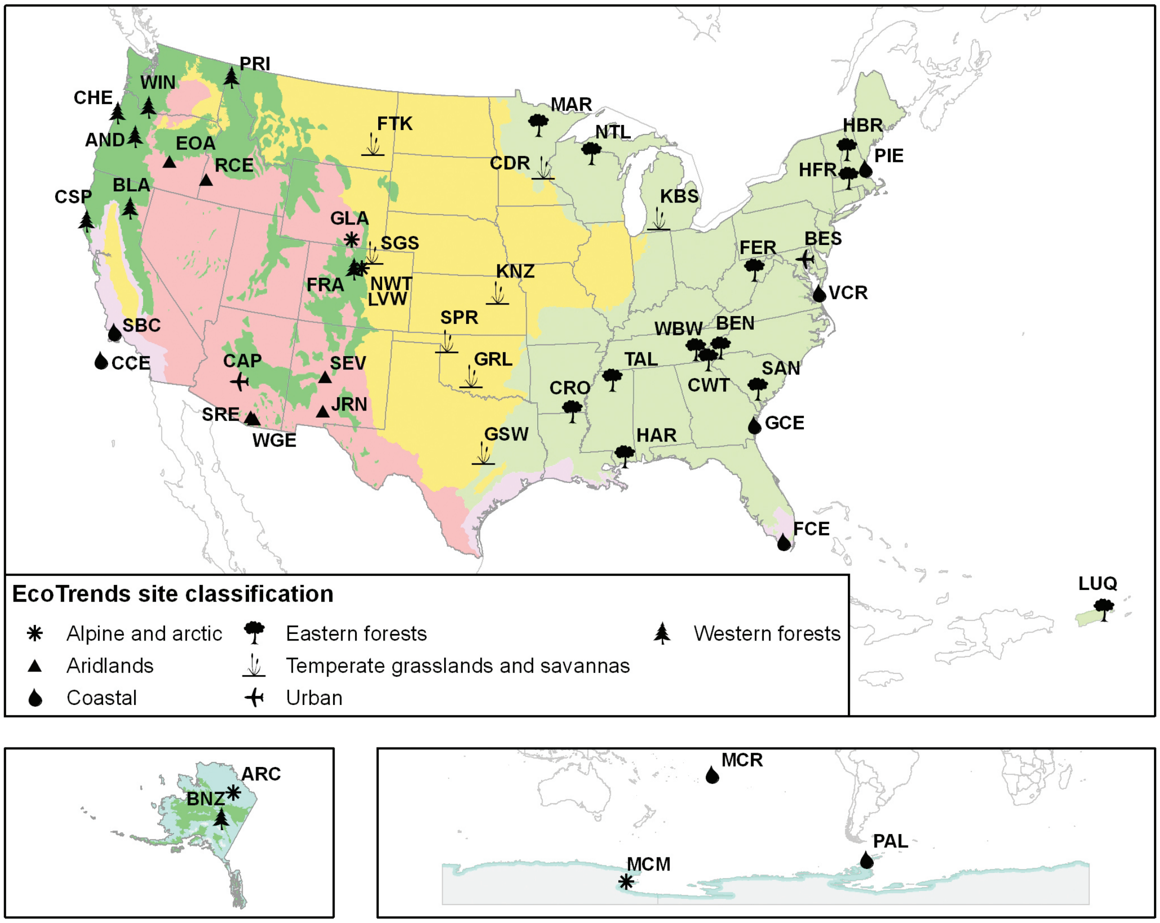

Figure 1-3. Location of sites shown by EcoTrends ecosystem type differentiated by symbols.
See table 1-1 for site names.

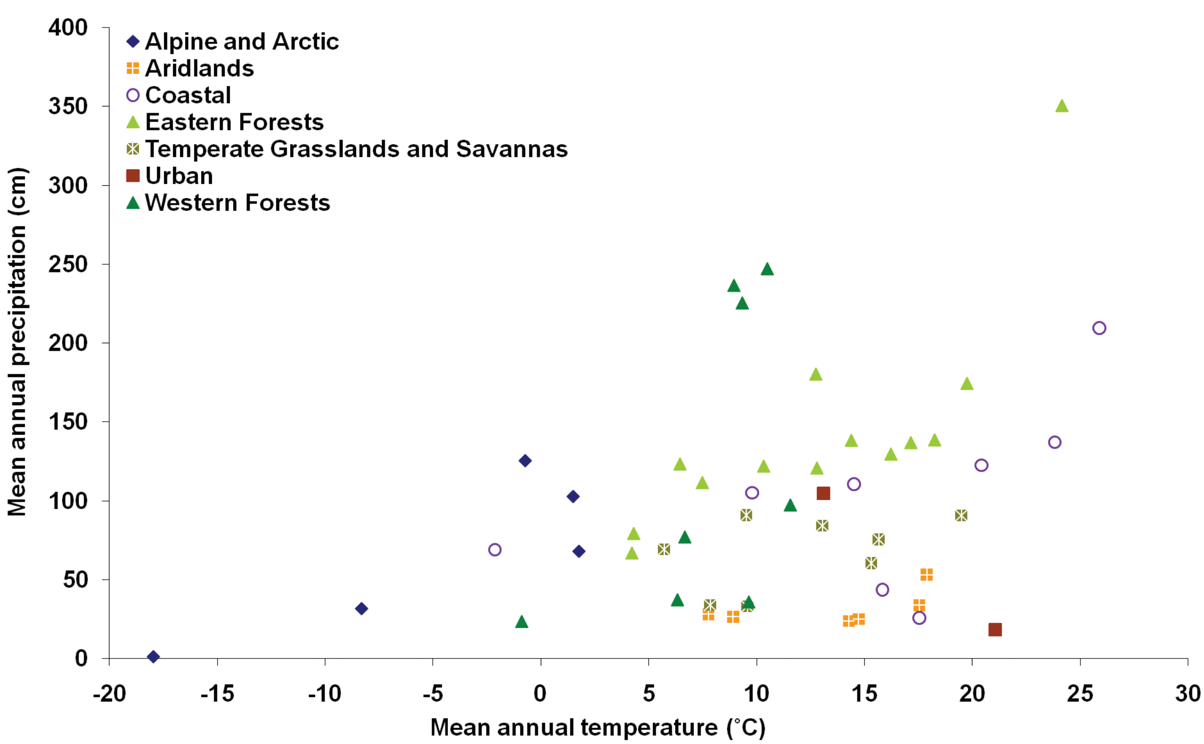

Figure 1-4. Mean annual temperature (°C) and precipitation (cm/y) of the 50 sites labeled by ecosystem type. Adjacent land area shown for coastal sites.

Data were obtained from one of three sources:

- Internet portals where data and metadata quality and standardization were already complete for many sites
- Individual research site web pages
- Individual researchers

Although data are often collected at more than one location within each research site, space constraints limit our analyses to a representative sampling location. We created derived data products by either averaging or summing the data from a single source, such as a weather station, or across a detailed study design to obtain one value per time step, which is typically a year or a month. Data and metadata in this book have undergone initial quality control for errors, have been formatted to a common standard, and are now available to the public from a single website (http://www.ecotrends.info). Users are encouraged to verify the accuracy of the data downloaded from the EcoTrends site by checking the original source of data.

Statistical Considerations

The original intent of this book (that is, to present the data in a straightforward, transparent manner to stimulate further exploration and analysis) guided the minimalist statistical treatment of the data. We present variables one at a time to allow readers to readily evaluate the data and compare datasets. We have not used ordination or classification methods, nor have we calculated multivariate measures of association. Our hope is that readers will be stimulated by the data presented in this book to conduct additional analyses on their own using data available on the EcoTrends website.

The exploration of long-term trends in measurements and the consistency of such trends across a range of measurement variables, biomes, and geographic regions involve significant challenges because of the need to present several hundred time-based series of diverse variables measured at different intervals. Measurement methods vary greatly and have an array of different error structures. Accordingly, to explore temporal trends in a consistent manner across all variables in the space allowed, we rely principally on simple linear regression methods using $p \leq 0.05$ as our level of significance. Probability values for the significance of linear regressions have not been corrected for the effects of serial autocorrelation (Pyper and Peterman 1998). We do not attempt to use alternative trend analysis or smoothing methods, either parametric or nonparametric, other than the calculation of a running mean for some variables. We test only for a linear relationship with time, although we are aware that some variables change in a nonlinear manner and higher order polynomials may be better descriptors of the underlying changes in certain datasets. In some cases, thresholds or relatively abrupt transitions may be apparent, but it was not practical to test for such responses across all variables. Again, we encourage readers to take the next steps on their own.

Organization of the Book

There are four main parts to this book. After a brief history (chapter 2), the first part consists of eight chapters (chapters 3-10) that illustrate the importance of long-term research across sites to address scientific questions or hypotheses. The research themes were selected based on their ecological importance and by the availability of long-term data for many sites, either previously published or in the EcoTrends database, that allow cross-site comparisons.

The second part consists of four chapters (chapters 11-14) that show long-term data and trends for each site. Each chapter contains a brief introduction to the topic and methods of measurements, selection of variables, and their data source. Each chapter consists primarily of a large number of figures showing long-term data for different variables. The figures are organized first by variable (for example, nitrogen), then by large-scale patterns in that variable across the country. For variables with many sites, we present the site-specific data through time for each ecosystem type. For variables with fewer than nine sites, we imbed the site graphs through time within a continental map to display broad-scale patterns in the variable.

The third part of this book consists of three chapters (chapters 15-17) containing management implications, recommendations for data accessibility in cross-site studies, and a synthesis of trends in the book followed by an identification of research needs.

The fourth part contains 28 appendices. Appendix 1 provides a short description of each site, and the other 27 appendices provide detailed information and summary statistics in a tabular format for each variable in chapters 11-14.

Table 1-1. Site names and codes with home page URL, funding agency and/or research program, and general characteristics

Site name (URL)	Site code[1]	Program/ agency[2]	MAP[3]	MAT[4]	Latitude	Longitude	Ecosystem type[5]
			cm	*°C*	°	°	
H. J. Andrews Experimental Forest (http://andrewsforest.oregonstate.edu/)	AND	USFS/LTER	226	9	44.21	-122.26	Western forests
Arctic (http://ecosystems.mbl.edu/ARC/)	ARC	LTER	33	-9	68.63	-149.60	Alpine and arctic
Baltimore Ecosystem Study (http://www.beslter.org/)	BES	USFS/LTER	105	13	39.10	-76.30	Urban (eastern forest)
Bent Creek Experimental Forest (http://www.srs.fs.usda.gov/bentcreek/)	BEN	USFS	122	13	35.48	-82.63	Eastern forest
Blacks Mountain Experimental Forest (http://www.fs.fed.us/psw/ef/blacks_mountain/)	BLA	USFS	--	--	40.67	-121.17	Western forest
Bonanza Creek Experimental Forest (http://www.lter.uaf.edu/)	BNZ	USFS/LTER	--	-1	64.80	-148.00	Western forest
California Current Ecosystem (http://ccelter.sio.ucsd.edu/)	CCE	LTER	26	18	32.87	-120.28	Coastal
Cascade Head Experimental Forest (http://www.fsl.orst.edu/chef/)	CHE	USFS	247	10	45.07	-123.97	Western forest
Caspar Creek Experimental Watershed (http://www.fs.fed.us/psw/ef/caspar_creek/)	CSP	USFS	102	11	39.38	-123.67	Western forest
Cedar Creek Ecosystem Science Reserve (http://www.lter.umn.edu/)	CDR	LTER	69	6	45.40	-93.20	Temperate grassland and savanna

Table 1-1. Site names and codes with home page URL, funding agency and/or research program, and general characteristics—*Continued*

Site name (URL)	Site code[1]	Program/ agency[2]	MAP[3]	MAT[4]	Latitude	Longitude	Ecosystem type[5]
			cm	*°C*	°	°	
Central Arizona-Phoenix (http://caplter.asu.edu/)	CAP	LTER	19	21	33.43	-111.93	Urban (Aridland)
Coweeta (http://coweeta.ecology.uga.edu/)	CWT	USFS/LTER	180	13	35.00	-83.50	Eastern forest
Crossett Experimental Forest (http://www.srs.fs.usda.gov/)	CRO	USFS	139	17	33.03	-91.95	Eastern forest
Eastern Oregon Agricultural Research Center (http://oregonstate.edu/dept/EOARC/)	EOA	ARS	28	8	43.50	-119.50	Aridland
Fernow Experimental Forest (http://www.fs.fed.us/ne/parsons/)	FER	USFS	128	10	39.05	-79.69	Eastern forest
Florida Coastal Everglades (http://fcelter.fiu.edu/)	FCE	LTER	141	24	25.47	-80.85	Coastal
Fort Keogh Livestock & Range Research Laboratory (http://ars.usda.gov/)	FTK	ARS	34	8	46.26	-105.53	Temperate grassland and savanna
Fraser Experimental Forest (http://www.fs.fed.us/rm/fraser/)	FRA	USFS	42	6	39.91	-105.88	Western forest
Georgia Coastal Ecosystems (http://gce-lter.marsci.uga.edu/)	GCE	LTER	131	20	31.43	-81.37	Coastal
Glacier Lakes (http://www.fs.fed.us/rmrs/experimental-forests/glacier-lake-ecosystem-experiments-site/)	GLA	USFS	132	-1	41.38	-106.26	Alpine and arctic

Table 1-1. Site names and codes with home page URL, funding agency and/or research program, and general characteristics—*Continued*

Site name (URL)	Site code[1]	Program/ agency[2]	MAP[3]	MAT[4]	Latitude	Longitude	Ecosystem type[5]
			cm	*°C*	°	°	
Grassland, Soil and Water Research Laboratory (http://ars.usda.gov/)	GSW	ARS	91	19	31.06	-97.20	Temperate grassland and savanna
Grazinglands Research Laboratory (http://ars.usda.gov/)	GRL	ARS	77	16	34.88	-98.00	Temperate grassland and savanna
Harrison Experimental Forest (http://www.srs.fs.usda.gov/)	HAR	USFS	176	20	30.63	-89.05	Eastern forest
Harvard Forest (http://harvardforest.fas.harvard.edu/)	HFR	LTER	111	8	42.50	-72.20	Eastern forest
Hubbard Brook Ecosystem Study (http://www.hubbardbrook.org/)	HBR	USFS/LTER	124	6	43.94	-71.75	Eastern forest
Jornada (http://jornada-www.nmsu.edu/)	JRN	ARS/LTER	26	15	32.62	-106.74	Aridland
Kellogg Biological Station (http://lter.kbs.msu.edu/)	KBS	LTER	91	9	42.40	-85.40	Temperate grassland and savanna
Konza Prairie Biological Station (http://www.konza.ksu.edu/)	KNZ	LTER	85	13	39.10	-96.40	Temperate grassland and savanna
Loch Vale Watershed (http://www.nrel.colostate.edu/projects/lvws)	LVW	USGS	103	2	40.29	-105.66	Alpine and arctic
Luquillo Experimental Forest (http://luq.lternet.edu/)	LUQ	USFS/LTER	351	24	18.30	-65.80	Eastern forest

Table 1-1. Site names and codes with home page URL, funding agency and/or research program, and general characteristics—*Continued*

Site name (URL)	Site code[1]	Program/ agency[2]	MAP[3]	MAT[4]	Latitude	Longitude	Ecosystem type[5]
			cm	*°C*	°	°	
Marcell Experimental Forest (http://nrs.fs.fed.us/ef/locations/mn/marcell/)	MAR	USFS	67	4	47.53	-93.47	Eastern forest
McMurdo Dry Valleys (http://www.mcmlter.org/)	MCM	LTER	1	-18	-77.00	162.52	Alpine and arctic
Moorea Coral Reef (http://mcr.lternet.edu/)	MCR	LTER	210	26	-17.48	-149.82	Coastal
Niwot Ridge Research Area (http://culter.colorado.edu/NWT/)	NWT	USFS/LTER	69	2	39.99	-105.38	Alpine and arctic
North Temperate Lakes (http://lter.limnology.wisc.edu/)	NTL	LTER	79	4	46.00	-89.70	Eastern forest
Palmer Station, Antarctica (http://pal.lternet.edu/)	PAL	LTER	69	-2	-64.70	-64.00	Coastal
Plum Island Ecosystems (http://ecosystems.mbl.edu/PIE/)	PIE	LTER	110	10	42.76	-70.89	Coastal
Priest River Experimental Forest (http://forest.moscowfsl.wsu.edu/ef/pref/)	PRI	USFS	79	7	48.35	-116.68	Western forest
Reynolds Creek Experimental Watershed (http://ars.usda.gov/)	RCE	ARS	27	9	43.08	-116.72	Aridland
Santa Barbara Coastal (http://sbc.lternet.edu/)	SBC	LTER	44	16	34.42	-119.95	Coastal

Table 1-1. Site names and codes with home page URL, funding agency and/or research program, and general characteristics—*Continued*

Site name (URL)	Site code[1]	Program/ agency[2]	MAP[3]	MAT[4]	Latitude	Longitude	Ecosystem type[5]
			cm	*°C*	°	°	
Santa Rita Experimental Range (http://cals.arizona.edu/SRER/)	SRE	U of A	56	18	31.80	-110.90	Aridland
Santee Experimental Forest (http://www.srs.fs.usda.gov/charleston/)	SAN	USFS	138	18	33.14	-79.79	Eastern forest
Sevilleta (http://sev.lternet.edu/)	SEV	LTER	24	14	34.35	-106.88	Aridland
Shortgrass Steppe (http://www.sgslter.colostate.edu/)	SGS	ARS/LTER	32	9	40.80	-104.80	Temperate grassland and savanna
Southern Plains Range Research (http://www.ars.usda.gov/)	SPR	ARS	63	15	36.62	-99.59	Temperate grassland and Station savanna
Tallahatchie Experimental Forest (http://www.srs.fs.usda.gov/)	TAL	USFS	140	17	34.50	-89.44	Eastern forest
Virginia Coast Reserve (http://amazon.evsc.virginia.edu/)	VCR	LTER	110	14	37.28	-75.91	Coastal
Walker Branch Watershed (http://walkerbranch.ornl.gov)	WBW	DOE	139	14	35.90	-84.30	Eastern forest
Walnut Gulch Experimental Watershed (http://www.tucson.ars.ag.gov/)	WGE	ARS	36	17	31.72	-110.68	Aridlands
Wind River Experimental Forest (http://www.fs.fed.us/pnw/exforests/wind-river/)	WIN	USFS	239	9	45.81	-121.98	Western forest

[1] Three-letter site codes used throughout this report; individual sites may use different acronyms.
[2] Program and agency abbreviations:
- DOE: Department of Energy
- LTER: Long Term Ecological Research Network
- ARS: USDA Agricultural Research Service
- USFS: USDA Forest Service
- USGS: U.S. Geological Survey
- U of A: University of Arizona

[3] MAP: mean annual precipitation.
[4] MAT: mean annual temperature.
[5] Natural ecosystems near cities are shown in parentheses for the two urban sites. NTL is the only lake ecosystem currently in EcoTrends; this site is classified as eastern forest to allow cross-site comparisons. "Eastern forest" and "western forest" are used to indicate location of the site either east or west of the Mississippi River.

Table 1-2. Site classification by EcoTrends ecosystem type and World Wildlife Fund terrestrial biomes, using same color codes to denote ecosystem types as those used in figures in chapters 11-13

EcoTrends ecosystem type	World Wildlife Fund biome[1]	Site code
Alpine and arctic	Temperate coniferous forests	GLA, LVW, NWT
	Tundra	ARC, MCM
Aridlands	Deserts and xeric shrublands	EOA, JRN, RCE, SEV, SRE, WGE
Coastal[2]	Flooded grasslands and savannas	FCE
	Mediterranean forests, woodlands, and scrub	CCE, SBC
	Temperate broadleaf and mixed forests	PIE
	Temperate coniferous forests	GCE, VCR
	Tropical and subtropical moist broadleaf forests	MCR
	Tundra	PAL
Eastern forests[3]	Temperate broadleaf and mixed forests	BEN, CWT, FER, HBR, HFR, MAR, NTL[4], TAL, WBW
	Temperate coniferous forests	CRO, HAR, SAN
	Tropical and subtropical moist broadleaf forests	LUQ
Temperate grasslands and savannas	Temperate broadleaf and mixed forests	KBS[5]
	Temperate broadleaf and mixed forests/ Temperate grasslands, savannas, and shrublands	CDR
	Temperate grasslands, savannas, and shrublands	FTK, GRL, GSW, KNZ, SGS, SPR
Urban[6]	Deserts and xeric shrublands	CAP
	Temperate broadleaf and mixed forests/ Temperate coniferous forests	BES
Western forests[3]	Boreal forests/Taiga	BNZ
	Temperate coniferous forests	AND, BLA, CHE, CSP, FRA, PRI, WIN

[1] http://wwf.panda.org/
[2] For coastal sites, terrestrial biomes are listed for the location of nearby land-based instrumentation (precipitation, temperature, precipitation chemistry).
[3] Forests are separated into two groups (western, eastern forests) for ease of presentation based only on their geographic location relative to the Mississippi River.
[4] NTL, a lake site, is classified here as eastern forest to allow cross-site comparisons.
[5] KBS, an intensive row-crop ecosystem site, is classified here as temperate grasslands and savannas to allow cross-site comparisons.
[6] For urban sites, the biomes of the surrounding natural ecosystems are given.

Table 1-3. Length of record of climate variables for each site

Site code	Air temperature	Precipitation	PDSI[1]	Ice duration	Sea level	Streamflow	Water clarity	Water temperature
AND	1958-2006	1958-2006	1895-2008	-	-	1953-2008	-	1977-2006
ARC	1989-2005	1989-2005	-	1988-2005	-	1983-2004	1989-2004	1975-2004
BEN	1949-2008	1949-2004	1895-2008	-	-	1935-1986	-	-
BES	1940-2008	1940-2008	1895-2008	-	1903-2008	1957-2007	-	-
BLA	-	-	1895-2008	-	-	-	-	-
BNZ	1989-2009	1990-2008	-	-	-	1969-2007	-	-
CAP	1894-2002	1894-2002	1895-2008	-	-	1941-2007	-	-
CCE	1927-2008	1927-2008	1895-2008	-	1906-2008	-	1969-2007	1917-2006
CDR	1893-2007	1837-2008	1895-2008	-	-	-	-	-
CHE	1950-2008	1949-2008	1895-2008	-	-	-	-	-
CRO	1916-2008	1916-2008	1895-2008	-	-	-	-	-
CSP	1935-2008	1913-2007	1895-2008	-	-	1986-2004	-	1989-2004
CWT	1943-2008	1944-2008	1895-2008	-	-	-	-	-
EOA	1937-2008	1937-2008	1895-2008	-	-	-	-	-
FCE	1950-2008	1950-2008	1895-2008	-	1913-2008	1964-2008	2000-2004	1993-2008
FER	1899-2006	1905-2006	1895-2008	-	-	1952-2007	-	-
FRA	1898-2006	1909-2006	1895-2008	-	-	1941-1984	-	-
FTK	1938-2008	1938-2008	1895-2008	-	-	-	-	-
GCE	1915-2008	1918-2008	1895-2008	-	1936-2008	1932-2008	-	2002-2008
GLA	1989-2005	1995-2005	1895-2008	-	-	-	-	-
GRL	1893-2006	1893-2006	1895-2008	-	-	-	-	-
GSW	1940-2008	1938-2008	1895-2008	-	-	1940-2008	-	-
HAR	1955-2004	1955-2006	1895-2008	-	-	-	-	-
HBR	1957-2007	1978-2008	1895-2008	1968-2005	-	1963-2007	-	-
HFR	1964-2008	1964-2008	1895-2008	-	-	-	-	-
JRN	1916-2008	1919-2008	1895-2008	-	-	-	-	-
KBS	1934-2008	1931-2008	1895-2008	1924-2006	-	1931-2009	-	-
KNZ	1899-2008	1898-2008	1895-2008	-	-	1980-2008	-	-
LUQ	1996-2004	1988-2004	-	-	1963-2008	1987-2006	-	-
LVW	1984-2006	1984-2006	1895-2008	-	-	1984-2004	-	1992-2006
MAR	1916-2007	1916-2007	1895-2008	-	-	1962-2006	-	-

Table1-3. Length of record of climate variables for each site—*Continued*

Site code	Air temperature	Precipitation	PDSI[1]	Ice duration	Sea level	Streamflow	Water clarity	Water temperature
MCM	1988-2007	1995-2006	-	-	-	1969-2004	-	1990-2005
MCR	1977-2007	1977-2007	-	-	1976-2008	-	-	-
NTL	1904-2008	1904-2008	1895-2008	1856-2008	-	1975-2007	1981-2007	1982-2008
NWT	1953-2006	1965-2006	1895-2008	1982-2006	-	1982-2001	-	-
PAL	1975-2008	1990-2008	-	1979-2006	-	-	-	-
PIE	1901-2008	1901-2008	1895-2008	-	1921-2008	1945-2009	-	-
PRI	1901-2008	1901-2008	1895-2008	-	-	1950-2008	-	-
RCE	1962-2007	1962-2007	1895-2008	-	-	1963-1995	-	-
SAN	1946-2005	1946-2007	1895-2008	-	-	1990-1999	-	-
SBC	1895-2006	1952-2007	1895-2008	-	1924-2008	1941-2007	-	1955-2004
SEV	1893-2008	1899-2008	1895-2008	-	-	-	-	-
SGS	1944-2008	1944-2008	1895-2008	-	-	-	-	-
SPR	1909-1976	1909-2007	1895-2008	-	-	-	-	-
SRE	1951-2004	1951-2004	1895-2008	-	-	-	-	-
TAL	1902-2008	1905-2008	1895-2008	-	-	-	-	-
VCR	1956-2007	1956-2007	1895-2008	-	1912-2008	-	1992-2008	-
WBW	1949-2008	1949-2008	1895-2008	-	-	1982-2005	-	-
WGE	1898-2007	1898-2007	1895-2008	-	-	1958-2008	-	-
WIN	1931-2009	1931-2008	1895-2008	-	-	-	-	-

[1] PDSI: Palmer Drought Severity Index.

Table 1-4. Length of record for each site for precipitation and surface water chemistry and for human population and economy variables

Site code	Precipitation chemistry	Water chemistry	Population and economy[1]
AND	1981-2008[2]	1982-2006[2]	1850-2000
ARC	1988-2003[2]	1990-2006[2]	1970-2000
BEN	1985-2008	--	1800-2000
BES	1984-2008[2]	1999-2008[2]	1790-2000
BLA	2000-2008	--	1870-2000
BNZ	1993-2008[2]	--	1970-2000
CAP	1999-2007[2]	1998-2008	1880-2000
CCE	--	1984-2005[2]	1850-2000
CDR	1997-2008	--	1860-2000
CHE	--	--	1860-2000
CRO	1983-2008	--	1850-2000
CSP	1980-2007	--	1850-2000
CWT	1979-2008	--	1820-2000
EOA	--	--	1890-2000
FCE	1982-2008	2001-2008	1830-2000
FER	1979-2008	1980-2006[2]	1860-2000
FRA	1984-2008	--	1880-2000
FTK	--	--	1880-2000
GCE	2004-2008	--	1790-2000
GLA	1986-2008	--	1870-2000
GRL	1984-2006	--	1910-2000
GSW	--	--	1860-2000
HAR	--	--	1850-2000
HBR	1979-2008	1965-2005[2]	1790-2000
HFR	1985-2008	--	1790-2000
JRN	1984-2008	--	1860-2000
KBS	1980-2008	--	1840-2000
KNZ	1983-2008	1985-2004[2]	1860-2000
LUQ	1986-2008	1986-2007[2]	1910-2000
LVW	1984-2008	1992-2006	1870-2000
MAR	1979-2008	--	1850-2000
MCM	--	1993-2007	-
MCR	--	--	-
NTL	1980-2008	1982-2007	1840-2000
NWT	1984-2008	1982-2006[2]	1870-2000
PAL	--	1994-2007[2]	-
PIE	1982-2008	1994-2003	1790-2000

Table 1-4. Length of record for each site for precipitation and surface water chemistry and for human population and economy variables—*Continued*

Site code	Precipitation chemistry	Water chemistry	Population and economy[1]
PRI	2003-2007	--	1910-2000
RCE	1984-2008	--	1870-2000
SAN	1985-2008	--	1890-2000
SBC	--	2001-2007[2]	1850-2000
SEV	--	--	1850-2000
SGS	1980-2008	--	1870-2000
SPR	--	--	1900-2000
SRE	--	--	1870-2000
TAL	1985-2008	--	1840-2000
VCR	1990-2007	1992-2007	1790-2000
WBW	1981-2008	1989-2005	1810-2000
WGE	2000-2008	--	1870-2000
WIN	--	--	1860-2000

[1] Earliest and latest years among all available data at a site are shown. There may be shorter lengths of record for some variables at a site.
[2] Not all years or variables were sampled. See appendix 27 for details.

Table 1-5. Length of record for each site for biotic variables

Site code	ANPP[1]	Production—other measures[2]	Aquatic production[3]	Plant biomass	Plant richness	Animal abundance[4]	Animal richness[5]
AND	1983-2005 [6]	-	-	1988-2005	1962-2008	1987-2007	-
ARC	1982-2000 [6]	-	1983-2004 [6]	1982-2000 [6]	-	-	-
BEN	-	1961-2001 [6]	-	-	-	-	-
BNZ	1991-1998	-	-	-	-	-	-
CAP	-	-	-	-	-	1998-2004 [6]	-
CCE	-	-	1984-2005	-	-	-	-
CDR	1982-1998	-	-	1988-2003	1988-2006	1989-2004	1989-2004
CHE	-	1935-2003	-	-	-	-	-
CRO	-	1948-2004 [6]	-	-	-	-	-
FCE	-	-	2001-2007 [6]	2001-2007 [6]	-	-	1996-2005
FTK	1993-2004	-	-	-	-	-	-
GCE	-	-	-	2000-2007	-	2000-2008	-
HAR	-	1960-2000	-	-	-	-	-
HBR	1987-1996	1965-2002	-	1965-2002	-	1969-2004 [6]	1969-2004
HFR	2002-2006	1969-2001	-	-	-	-	-
JRN	1990-2008	-	-	-	1989-2008	1995-2008 [6]	-
KBS	1991-2008 [6]	-	-	-	1991-2008 [6]	1989-2008	-
KNZ	1984-2005	-	-	-	-	1981-2004 [6]	1982-2004
LUQ	-	-	-	-	-	1987-2008 [6]	-
MCM	-	-	1989-2007 [6]	-	-	-	-
MCR	-	-	1998-2008	-	-	2000-2008	2000-2008
NTL	-	-	1987-2007	1983-2008	1983-2008	1981-2008	1981-2008
NWT	1982-1997	-	-	-	-	-	-
PAL	-	-	1991-2006	-	-	1975-2008	-
PIE	1985-2005 [6]	-	-	1984-2005	-	-	-
SBC	-	-	-	2002-2008	-	-	-
SEV	1999-2008 [6]	-	-	-	1999-2008 [6]	1989-2008	-

Table 1-5. Length of record for each site for biotic variables—*Continued*

Site code	ANPP[1]	Production—other measures[2]	Aquatic production[3]	Plant biomass	Plant richness	Animal abundance[4]	Animal richness[5]
SGS	1983-2007 [6]	-	-	-	-	1995-2008	1994-2008 [6]
SPR	-	-	-	1984-2005	-	-	-
SRE	-	-	-	-	1972-2006	-	-
VCR	-	-	-	1993-2006	-	1989-2004	-
WGE	-	-	-	-	1967-2007 [6]	-	-

[1] ANPP: Aboveground Net Primary Production.

[2] Production: other measures include diameter at breast height (DBH), tree height, tree volume, and seed production.

[3] Aquatic production includes chlorophyll A concentration and primary production.

[4] Animal abundance includes aquatic animals (crayfish, fish, frogs, shrimp, snails), birds, insects, and mammals.

[5] Animal richness includes birds, fish, and insects.

[6] Not all years were sampled for all stations. See appendix 28 for details.

Chapter 2

History and Organization of the Ecotrends Project

C.M. Laney, D.P.C. Peters, and K.S. Baker

Cross-site synthesis initiatives offer important opportunities for learning. The internal organizations and histories of these projects are not always documented in detail, but their lessons can inform future projects or sites that would like to participate in larger projects (chapters 16 and 17). In this chapter, we describe the internal organization and timeline of the EcoTrends Project as background to the data and recommendations that follow in subsequent chapters.

The EcoTrends Project began in 2004 when two scientists (Debra Peters and Ariel Lugo) saw a need to synthesize, and make easily accessible, long-term datasets to compare continental-scale and national-level trends in ecological responses to changing environmental drivers (figure 2-1). Because Peters (of USDA, Agricultural Research Service [ARS]) and Lugo (of USDA, Forest Service) are employed by different Federal agencies with existing networks of sites and were actively involved in the Long Term Ecological Research (LTER) program, the EcoTrends project began as a multiagency collaboration, initially funded by ARS. The project's organizational structure expanded over the next 6 years to include many activities and dozens of individuals from six major groups.

Project Organization

Broad organizational structures and a well-defined set of objectives and communication processes were needed to make the project successful. These arrangements were a critical aspect of the project because of the data management differences between sites and agencies as well as the large variety and number of datasets. The six major groups (figure 2-2) each contributed to infrastructure and produced new knowledge and data products (table 2-1):

1. The EcoTrends Project Office (EPO) in Las Cruces, NM, consisted of a director (scientist) (D. Peters), a project coordinator (C. Laney), a spatial analyst (J. Yao), and several graduate and undergraduate student assistants. The information manager of the Jornada Basin LTER (JRN) (K. Ramsey) assisted with designing, building, and maintaining the in-house information management system. The EPO provided overall direction and leadership for the project and worked closely with the other five entities to assemble, correct, and verify long-term data and metadata; to create the derived data products; to coordinate documentation of the derived datasets; and to make them publicly available via a website (http://www.ecotrends.info). ARS and JRN began funding work at EPO in 2004. National Science Foundation supplements to the JRN site provided support for the period 2006-2009.
2. The EcoTrends Editorial Committee (EEC) was formed in 2005 and consisted of a group of 12 scientists (authors of this book) with different expertise (including population ecology and biogeochemistry) and experience with different habitat types (such as lakes, urban, forests, grasslands, oceans) or system components (plants, animals, soils). Members of this committee sorted through the vast amounts of historic and ongoing data from all 50 sites and made decisions about the variables to be included and the content and organization of the book and the website.
3. The EcoTrends Technical Committee (ETC) was also formed in 2005 and consisted of a group of nine computer scientists and information managers drawn from the LTER Network Office, the National Center for Ecological Analysis and Synthesis (NCEAS), and the LTER information managers. Members of this committee provided advice on data and metadata best practices and functionality of the website. The members of this committee are the technical consultants for this book.
4. Participating site scientists, information managers, and technical staff were engaged in the project at various times and provided their datasets to EPO, verified data quality and quantity, and assisted EPO in creating corrected, derived datasets. They provided important insight into the needs of site personnel, issues with creating and comparing derived datasets, and the lessons learned while building their own information management systems and while coordinating data and information transfer with other sites.

2004

- EcoTrends Project initiated
- EPO unsuccessfully attempted unassisted data collection from websites
- EPO emailed requests to solicit data from selected lead researchers
- Book endorsed by LTER Publications Committee

2005

- EcoTrends Project approved as an LTER Network Information System (NIS) module by the LTER Coordinating Committee
- Project Coordinator hired, EEC and ETC formed

2006

- EPO emailed another solicitation for data to all site lead researchers and information managers
- Dialogue between project coordinator and sites initiated
- Key attributes list finalized by the EEC
- Internal website developed by the JRN to help the EEC view accumulated datasets
- LTER ASM talks: Keynote by EcoTrends PI, presentation by EcoTrends Project coordinator to the LTER information manager community, and presentation by LNO developer on the infrastructure to support the website.
- Infrastructures , databases and website designed
- Data derivation started

2007

- Development of infrastructures , databases and website started
- Initial population of website databases started
- EcoTrends Project included in LTER Decadal Plan
- Data derivation continued

2008

- Book prospectus approved by USDA for publication
- Website opened to site researchers and information managers for data checking
- Spreadsheet reporting system created to support data checking process
- Data derivation continued

2009

- Data derivation continued
- Data check by sites for data represented in the book
- Six science-driven working groups met to work on science products
- Website and datasets made publicly available
- EcoTrends working groups met at the All Scientist's Meeting

2010

- Book manuscript finalized with community input, reviewed, and submitted to the USDA ARS publisher
- EcoTrends website reloaded with clean derived data and released to the public domain.

Figure 2-1. EcoTrends timeline from 2004 to 2010.

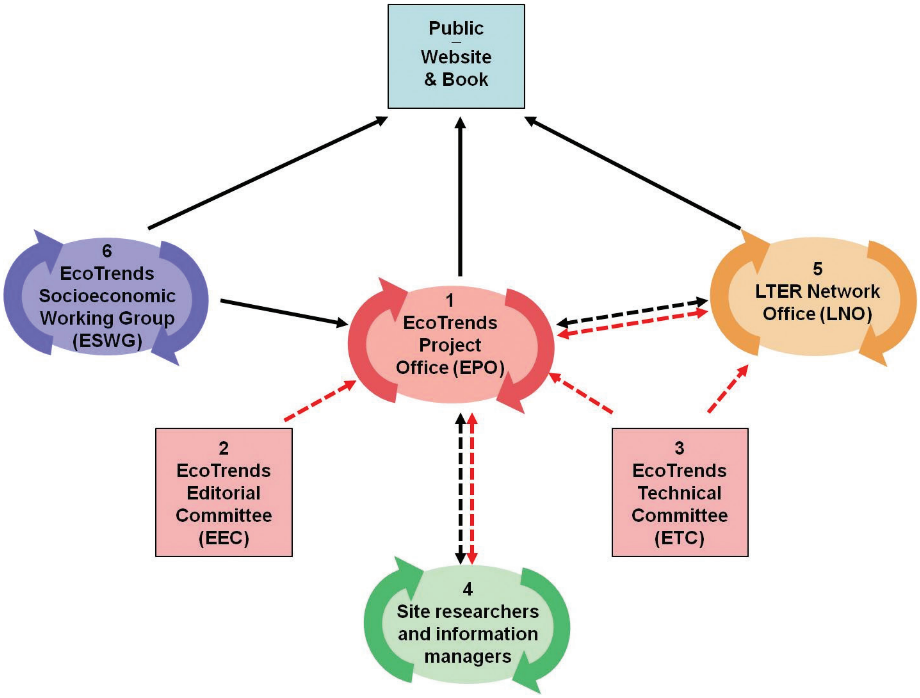

Figure 2-2. EcoTrends organizational arrangements and products. Each work arena is depicted by an ellipse with thick curved arrows that represent internal, dynamic information systems. The advisory committees are shown as rectangles. Straight arrows indicate interactions between the work arenas. Solid black arrows show dataset transfer. Dashed black arrows depict communications between arenas about data issues. Dashed red arrows depict flow of advice.

5. The LTER Network Office (LNO) formed parts of the EEC and ETC, helped design the EcoTrends website, developed routines to create derived dataset documentation and to support website functionality, and deployed the website from its local servers. LNO provided travel support for meetings of the EEC in 2006-08. National Science Foundation supplements to LNO supported work from 2006 to 2009.
6. The EcoTrends Socioeconomic Working Group (ESWG) was composed of one member of the EEC (J. Grove) and two LTER scientists (T. Gragson and C. Boone). This group used supplemental funding from the U.S. Department of Agriculture, Forest Service and National Science Foundation to New Mexico State University to compile historical census data for the participating sites (comprising about 1,000 counties and 32 variables) from several sources. This group also developed a complementary website, the LTER Socioeconomic Catalog (table 2-1), to make these data publicly accessible. A subset of these data were used in this book and are posted on the EcoTrends website.

Timeline

Gathering datasets took a substantial amount of time and effort by a large number of participants in all six groups. Dataset gathering began in 2004 when an undergraduate student from New Mexico State University was hired to find, download, and document long-term datasets (10 years or longer) from websites of research sites. However, this task was more substantial than anticipated. Few web pages provided tools to differentiate long-term datasets within large data stores. Some datasets were insufficiently documented or quality checked and verified for accuracy. Accordingly, the EPO was expanded in 2005 to include a project coordinator and a support position at JRN. ECC and ETC were formed to help assess the status of the data gathering effort and to solicit further contributions. In addition, the project was approved as an LTER Network Information System module (Brunt 1998, Baker et al. 2000) by the LTER Network governing body (the LTER Coordinating Committee), and the book was approved as an LTER publication by the LTER Publications Committee.

Prior and subsequent to the ECC's first meeting in 2006, email solicitations for datasets, without restriction on variable type or documentation level, were sent to the lead scientist at each site. At some sites, requests were handled by the lead scientist or a team of ecologists. At other sites, the request was transferred to the site information manager who often responded

Table 2-1. EcoTrends entities: knowledge, infrastructure, and data products[1]

EcoTrends entities	Knowledge products	Infrastructure products	Data products
EcoTrends Project Office (EPO)	Synthesis book	Local database, project-level data repository	Derived datasets with metadata
EcoTrends Editorial Committee (EEC)	Cross-site scientific publications; advice for website front end and the EPO	Interactions and support between site researchers	Selection of data products
EcoTrends Technical Committee (ETC)	Technical publications; advice for website back end	Interactions and support between site information managers, LNO, and EPO	
Site researchers, information managers	Scientific publications	Information systems, including data repositories and digital libraries	Original datasets with metadata
LTER Network Office (LNO)	Technical publications	Information system, data repository, and website	
EcoTrends Working Group (ESWG)	Cross-site scientific publications	LTER Socioeconomic Catalog database and website	Population and economy datasets

[1]A distinction is made here between knowledge products (such as scholarly works), infrastructure products (such as database or website development), and data products (such as data tables, metadata documents, and graphs) (Gibbons et al. 1994, Hine 2006).

by sending datasets or links to online datasets. Several hundred datasets were submitted that were then categorized by common variable (such as temperature, nitrogen deposition, or plant cover) and examined for consistency among sites by the ECC. Where critical datasets appeared to be missing, followup e-mail requests were sent to the site contacts to check the availability of the datasets, resulting in further submissions.

In addition to the directly submitted datasets, data from other organizations were downloaded from public websites (See table 2-2 for definitions of acronyms and Internet links). Climate and hydrological data were downloaded from the LTER Climate Database (Henshaw et al. 2006), the National Climate Data Center (NCDC), the National Oceanic and Atmospheric Administration (NOAA), and the United States Geological Survey (USGS). Atmospheric chemistry data were downloaded from the National Atmospheric Deposition Program (NADP). The ESWG coordinated the downloading and processing of human population and economy data from the InterUniversity Consortium for Political and Social Research and GeoLytics (http://www.geolytics.com/). A nearly complete working list of key variables and datasets was agreed upon at the ECC and ETC meeting in July 2006 and confirmed at the following meeting in February 2007.

From 2006 to 2008, solicitation of site-level datasets continued while computer programs in R (http://www.r-project.org) were written to process and graph the data. Throughout this period, EEC communicated frequently with EPO to review data progress and make recommendations on further work. In 2008, EPO asked the LTER community to review source and derived datasets online in the form of tables and graphs. Dataset review was divided into several stages. Sites were first asked to check the derived climate, biogeochemistry, and human population data and some months later to review the complete set, including biological data. Site personnel were asked to review and update their source data when necessary.

Dialogue among members over design issues progressed over several years of database and website design and implementation. At the EPO, a database, a data store, and a versioning repository system were developed to track the source data, manage the derivation processes, and document the derived datasets. A local website was developed at JRN to assist with database management, to allow EEC to review book graphics remotely, and to comment on the products and overall progress of the project. The design process for the EcoTrends website also began. A website designer was contracted, and the initial website design was sent to LNO for refinement and implementation. LNO designed and developed an automated system for harvesting each derived dataset and associated metadata into the databases underlying the website, using the EPO database and file naming structures, and for generating an Ecological Metadata Language (EML) documentation file for each derived data product. LNO also built the underlying website structure and tools necessary for data searching, browsing, viewing, and visualizing graphically.

In 2009-2010, EPO tested the usefulness of the derived data and website through six scientist-led working groups. These groups, each working with a different theme, explored how synthesis of EcoTrends-derived datasets could inform research. Each group also explored the EcoTrends data repository, downloaded useful data from the website, and analyzed these data in the context of other non-time-series data. This exercise resulted in valuable feedback about the usability of the website and the data it contains.

Near the end of 2009, EPO asked all participants to extensively check in detail the graphics presented in this book, the derived data, and the associated content on the EcoTrends website, providing another opportunity for community-level participation. Each chapter of this book was written by a small set of site participants and posted online for review by all site participants. An early version of the EcoTrends website was made available to the participants to explore datasets, provide recommendations on future website redesign, and comment on missing data types. Although sites had been asked several times over the past couple of years to check their data, this final check elicited further feedback from the community, likely stimulated by the immediacy of seeing their data and text in print.

Table 2-2. EcoTrends project-related organizations: acronyms or terms and Internet links

Acronym/term	Name	Link
EML	Ecological Metadata Language	http://knb.ecoinformatics.org/software/eml/
EPA	Environmental Protection Agency	http://www.epa.gov
FGDC	Federal Geographic Data Committee	http://www.fgdc.gov
GeoLytics	GeoLytics demographic data	http://www.geolytics.com
ICPSR	Inter-University Consortium for Political and Social Research	http://www.icpsr.umich.edu
LNO	LTER Network Office	http://lno.lternet.edu
LTER	Long Term Ecological Research Network	http://www.lternet.edu
EcoTrends Socioeconomic Catalog	EcoTrends Socioeconomic Catalog	http://coweeta.uga.edu/trends/
Metacat	Ecoinformatics Metadata Catalog	http://knb.ecoinformatics.org
NADP	National Atmospheric Deposition Program	http://nadp.sws.uiuc.edu
NCDC	National Climatic Data Center	http://www.ncdc.noaa.gov
NOAA	National Oceanic and Atmospheric Administration	http://www.noaa.gov
R	R project for statistical computing	http://www.r-project.org
ARS	United States Department of Agriculture, Agricultural Research Service	http://www.ars.usda.gov
USFS	United States Department of Agriculture, Forest Service	http://www.fs.fed.us/

Contributions to Information Management

A set of formalized databases and communication systems were needed to address organizational and technological challenges of managing the hundreds of submitted and downloaded datasets (source datasets) within and between EPO and LNO. As projects of this size and scope are complex and relatively rare, advice on how best to proceed was needed from a broad community. ETC advised EPO and LNO on technical issues, data management practices, organizational mechanisms, and website development. Presentations made at various meetings engaged participants and elicited further input from the science and information management communities. EcoTrends information management also drew upon participants' past experiences with collaborative, cross-site research activities and existing network infrastructures, principally LTER.

Experience gained through data handling, web development, and technology committee and information management community discussions motivated the development of other LTER Network-level cyberinfrastructure projects, principally the Provenance-Aware Synthesis Tracking Architecture (PASTA) (Servilla et al. 2006, 2008). PASTA was conceived and prototyped to support the EcoTrends website, originally as the tool to automate harvesting of the derived data into a repository that was accessible to the website. The EcoTrends experience also contributed to further development of EML and of Metacat, a system developed by the Knowledge Network for Biocomplexity for cataloging EML documents.

Conclusions

The EcoTrends Project is a scientist-driven initiative that has, since 2004, drawn upon a large and diverse community of researchers, information managers, and computer scientists for advice and support. Interactive cycles of refinement were based on community feedback and lessons learned. Where possible, the project attempted to use and support further development of community data practices and metadata standards, while maintaining flexibility for datasets that did not fully meet these practices or standards. This approach facilitated an evolving trend toward data sharing and synthesis. Lessons learned throughout the process (chapters 16 and 17) will inform future multiagency, cross-site, multidisciplinary projects.

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Chapter 3

Cross-Site Comparisons of Ecological Responses to Climate and Climate-Related Drivers

M.D. Ohman and T.K. Kratz

Climate (the average and variability of weather conditions over a period of time) is a primary driver of ecological systems. Important climate and climate-related factors for ecosystems include precipitation, air and water temperature, ice cover duration, sea level, stream flow, solar radiation, and water clarity. These factors affect resources available to plants, animals, and microbes and act as environmental constraints on the suitable habitat for reproduction, growth, and survival of organisms. Changes in seasonal and annual climatic patterns can have important consequences for key ecosystem properties, such as species composition and diversity, phenology, migrations, trophic interactions, rates of nutrient cycling, and net primary production.

Long-term data are required to differentiate directional climate trends from short-term pulses and natural variability in climate. Globally over the past century, temperatures have warmed in the atmosphere, on land, in the ocean, and in the cryosphere (IPCC 2007). In addition to this background of progressive long-term change, there are multidecadal-scale variations associated with phenomena such as the Pacific Decadal Oscillation (PDO) and North Atlantic Oscillation (NAO), as well as interannual variations dominated by the El Niño-Southern Oscillation (ENSO).

Understanding ecological responses to climate change is difficult because of the interactions among climate drivers on these multiple time scales. In addition, ecological systems respond to multiple drivers (such as climate and land use change) simultaneously, and these responses are often nonlinear. It is often difficult to perform large experiments in which climate is manipulated in controlled ways. Thus, long-term observations of ecological systems are critical to improving our understanding as to how a wide range of ecological phenomena respond to changes in climate at timescales ranging from multiple years to decades and centuries (Greenland et al. 2003).

In this chapter, we illustrate the value of long-term data in testing two ecological hypotheses related to climate change for different ecosystems. The relationship between changes in climate, responses of ecosystems and their constituent populations, and the services that ecosystems provide is the subject of considerable contemporary research. We do not attempt a listing of the diverse hypotheses that are possible, but rather we illustrate the value of long-term data from a geographically dispersed network of research sites in testing hypotheses with different time scales of climate change: (1) interannual variations forced by ENSO and (2) longer term, multidecadal changes. In the case of ENSO, the examples illustrate the power to assess qualitatively different types of ecosystem responses to a common climate driver. Additional examples of ecological responses to climate can be found in Greenland et al. (2003). Graphs of long-term climate data for each site are shown in chapter 11.

Hypothesis 1: El Niño-Southern Oscillation (ENSO) Alters Populations and Food Webs in Both Ocean and Terrestrial Biomes

Characteristics of the climate driver. ENSO constitutes one of the major climate signals on Earth and has effects that can extend globally. El Niño refers to large, positive anomalies in temperature across the eastern tropical Pacific Ocean, while La Niña refers to negative temperature anomalies in the same region. Corresponding changes in the atmosphere are known as the Southern Oscillation, which arise from variations in the west-to-east Walker Circulation in the equatorial Pacific.

The Southern Oscillation Index is based on differences in atmospheric pressure between the eastern tropical Pacific (at Tahiti) and the western tropical Pacific (Darwin, Australia). A negative state of the SOI implies a weakened atmospheric high pressure zone in the eastern Pacific, diminished Walker Circulation, and weakened westward-flowing winds, which are accompanied by warm ocean El Niño conditions in the western Pacific. A positive state of the SOI implies an intensified atmospheric high in the eastern Pacific, stronger than normal westward flowing winds, and anomalously cool La Niña ocean conditions in the western Pacific.

In recent decades, ENSO has recurred about every 2-7 years. It has been suggested that the strength of the Walker Circulation, whose variations affect ENSO dynamics, has decreased approximately 3.5 percent in the past 150 years as a consequence of human-induced climate change through greenhouse gas emissions (Vecchi et al. 2006). Other evidence suggests equatorial ocean responses may differ from those in the atmosphere (Karnauskas et al. 2009). If changes do occur in the frequency of occurrence and magnitude of ENSOs, we can expect consequences for numerous ecological processes in diverse ecosystems.

ENSO has consequences for the Earth's climate far from the tropics because its effects can propagate through both the ocean and the atmosphere. From the eastern tropical Pacific, warm El Niño temperature anomalies move poleward along the eastern ocean margin in both the northern and southern hemispheres. ENSO-related changes of atmospheric circulation can extend to middle latitudes and even polar regions through long-distance atmospheric teleconnections. Combined ocean and atmospheric changes affect temperature, winds, sea level, and rainfall patterns—and therefore droughts and forest fires—in regions distant from the equator.

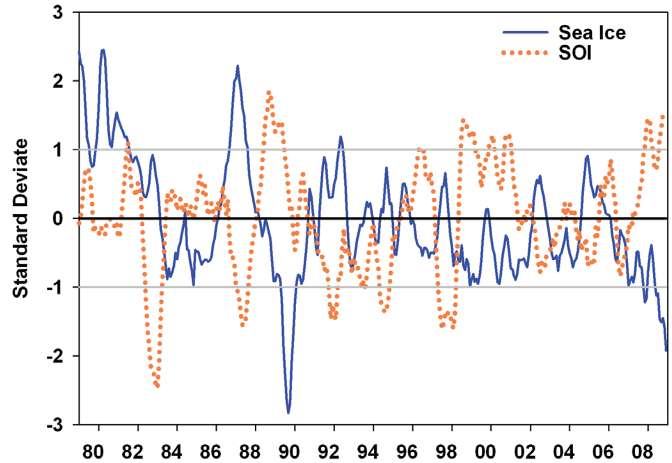

Figure 3-1. Normalized anomalies of a Sea Ice Index from the PAL LTER site (solid line) and the Southern Oscillation Index (SOI) (dashed line). (Adapted from Stammerjohn et al. 2008.)

Ecosystem Responses to ENSO

Adélie penguin foraging success in the Southern Ocean. Studies in the Palmer Station LTER site (PAL) on the Western Antarctic Peninsula have shown that interannual variations in sea ice extent are related to variations in ENSO, as reflected by the SOI (figure 3-1). A positive SOI during La Niña conditions is associated with decreased spatial coverage of sea ice, while a negative SOI during El Niño is associated with increased sea ice, principally through changes in the timing of sea ice advance and retreat (Stammerjohn et al. 2008). Such changes have important consequences for penguins and their primary prey, Antarctic krill.

The increased sea ice coverage during the El Niño phase favors Adélie penguins, but not the ice-avoiding Gentoo and Chinstrap penguins (Fraser and Hofmann 2003, Smith et al. 2003, Ducklow et al. 2007). Increased sea ice is associated with enhanced krill recruitment and therefore better foraging conditions for Adélies at their breeding colonies (Fraser and Hofmann 2003). In addition, Adélies are flightless and do not forage at night, so their ability to search the marine environment during polar winter is limited. Their foraging range and feeding success is constrained to particular regions ("hotspots") of the Western Antarctic Peninsula where krill patches recur and where prey availability is predictable over ecological time scales (decades to centuries) (Fraser and Trivelpiece 1996). If sea ice does not develop near these hotspots or its duration is too short, as typically occurs during the La Niña phase, then Adélie penguins cannot access key winter foraging areas, and their mortality increases (W. Fraser et al., unpublished data).

In addition to the relationship between ENSO and Adélie foraging success on an interannual scale, long-term changes in the frequency of occurrence of La Niña conditions have been associated with a precipitous decline in the Antarctic Adélies and an increase in the numbers of sub-Antarctic Gentoos and Chinstraps (figure 4-2) (Ducklow et al. 2007). This shift in dominant penguin species is resulting in state changes with important consequences for other parts of the ecosystem (McClintock et al. 2008).

Zooplankton trophic shifts off the Southern California coast. Food webs in the currents off the coast of California are strongly influenced by ENSO events via changes in both the ocean and the atmosphere. Kelp forest canopies are removed during strong winter ENSO storms, and the surviving plants become nutrient starved as nitrate-rich waters remain too deep in the water column to be accessible to the growing kelp (Dayton and Tegner 1984). Phytoplankton are also affected adversely, as vertical fluxes of nutrients into the euphotic zone appear to be reduced through a deepening of the region of elevated nitrate concentrations (Goericke et al. 2007), accompanied by a contraction of the area of coastal upwelling (Kahru and Mitchell 2000).

Such ENSO-related changes in nutrient supply and phytoplankton primary production are also reflected in reduced biomass of zooplankton (Chelton et al. 1982, Lavaniegos and Ohman 2007). Food web structure is also modified, as reflected in stable nitrogen isotopes of zooplankton from the California Current Ecosystem site (CCE). For three of four zooplankton species examined, the animals became isotopically heavier in the spring of major El Niño years relative to the spring of preceding and following years (figure 3-2). One of the two species of omnivorous copepods *(Calanus pacificus)* shows such an effect, while the other *(Eucalanus californicus)* does not because of interspecific differences in life history.

Both of the carnivorous chaetognath species show enrichment of the heavier nitrogen isotope of 1-2 per mil, which illustrates that the effects of ENSO are measureable at the level of primary carnivores. These isotopic shifts of zooplankton during El Niño conditions occur because of altered nitrogen sources for the phytoplankton at the base of the food web, with an apparent change in the nitrate supply relative to ammonium (Rau et al. 2003).

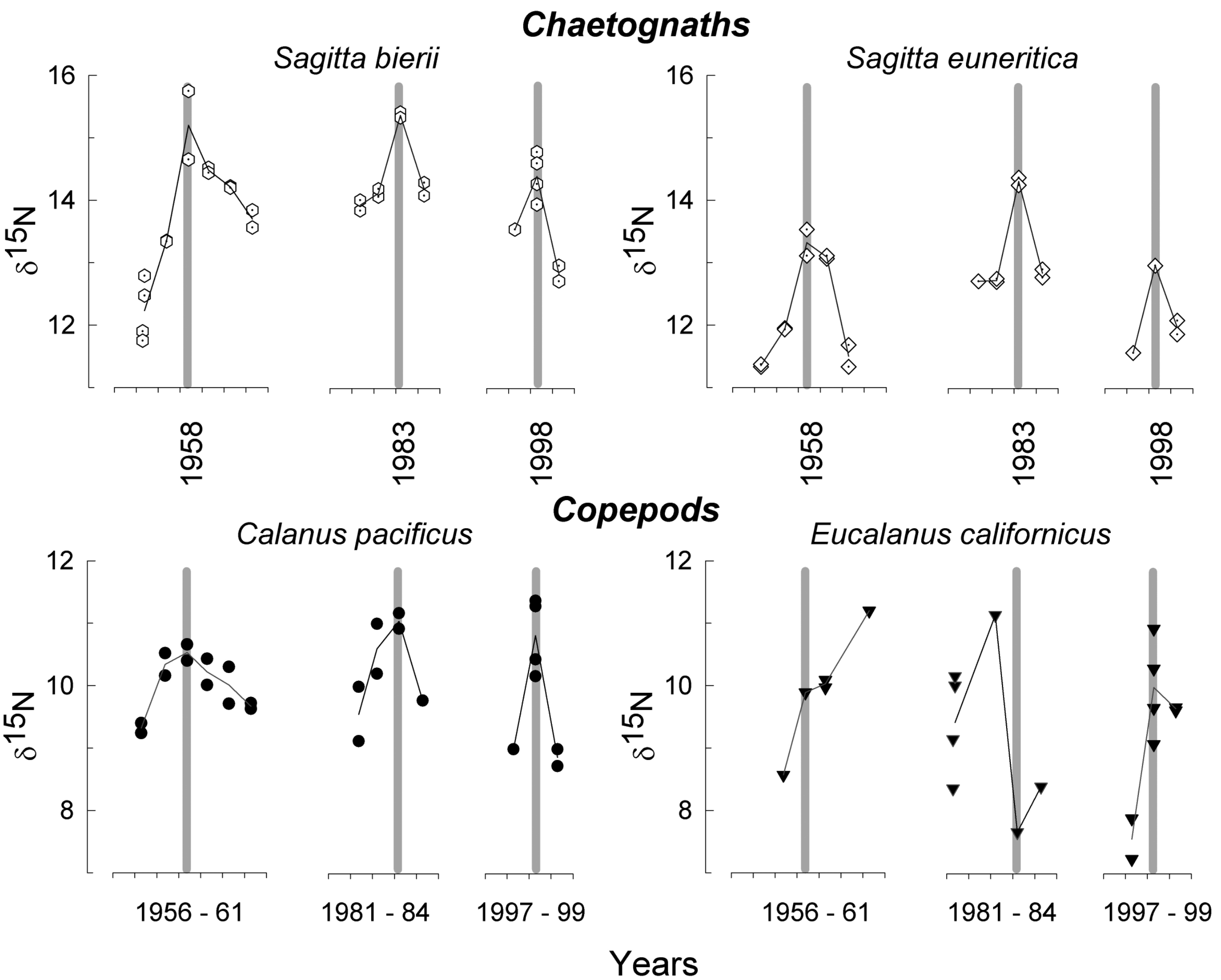

Figure 3-2. Springtime stable nitrogen (N) isotope content of four species of zooplankton from the CCE LTER region. Grey bars indicate major El Niño years (1958, 1983, 1998) (Rau et al. 2003). Reprinted with permission from Elsevier.

Hantavirus in deer mice from the southwestern desert. In a remarkable linkage between ENSO and human disease, Yates et al. (2002) documented the rodent-vectored hantavirus outbreak in the southwestern United States and its connection to El Niño. The primary vectors of the hantavirus are deer mice (*Peromyscus* spp.), whose populations have been studied at the Sevilleta LTER site (SEV) since 1989. During El Niños in 1992-1993 and 1997-1998, winter precipitation increased markedly, especially in the fall to spring period. Increased precipitation increased soil moisture content and primary production, and resulted in enhanced food supply for deer mice (Yates et al. 2002). An increase in population density of deer mice lagged the precipitation increase by one year, and was followed by an increase in density of virus-infected deer mice and resulting increase in incidence of the disease in humans after an additional 1-2 year lag (figure 3-3). Thus, ENSO-related changes in precipitation led to an expansion of numbers of infected mice and density-dependent increase of human infection.

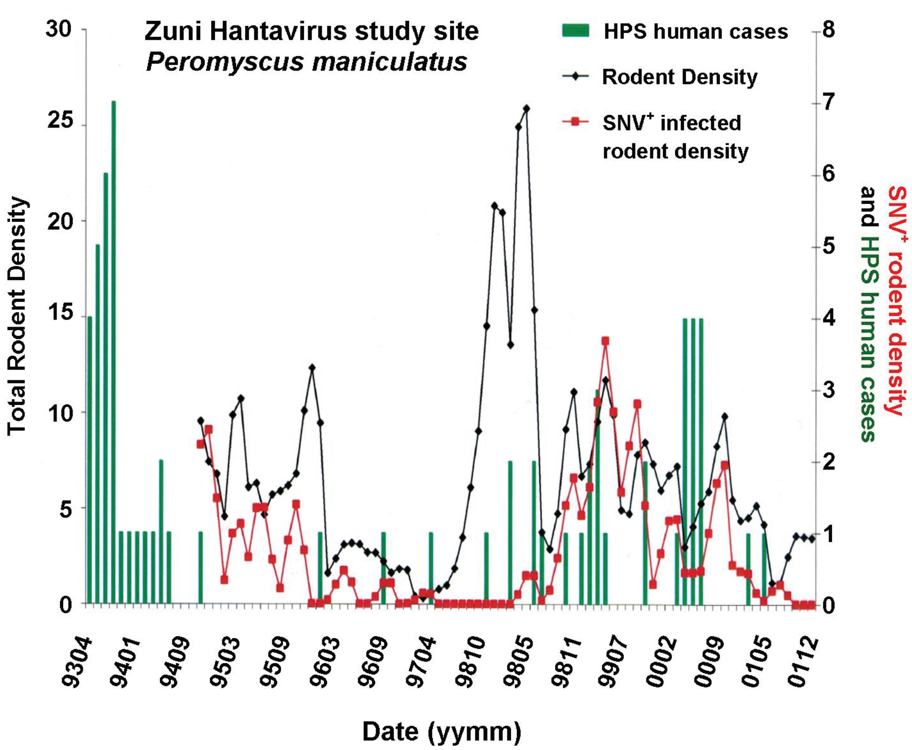

Figure 3-3. Densities of deer mice near Zuni, NM (black line), and densities of deer mice infected with Sin Nombre virus (SNV) at the same localities (red line). Human Hantavirus pulmonary syndrome (HPS) cases (green histograms) from the five counties surrounding Zuni and near the SEV LTER (Yates et al. 2002). Reprinted with permission from the American Institute of Biological Sciences.

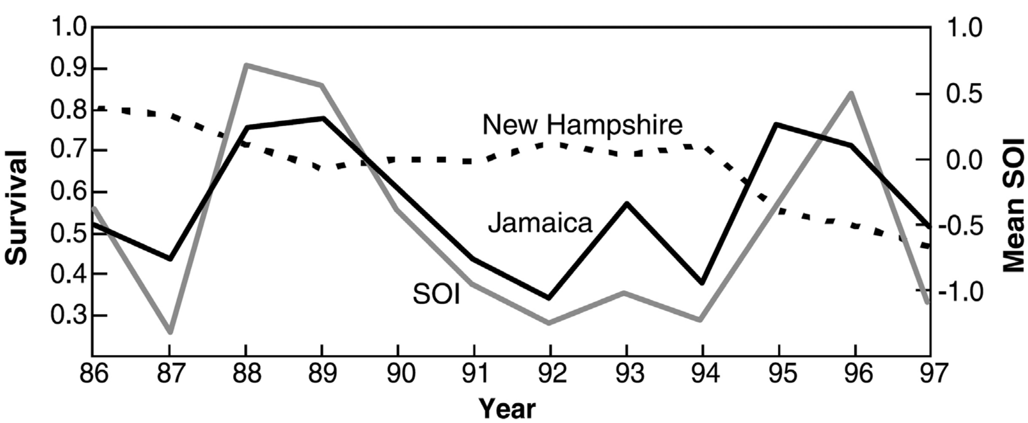

Figure 3-4. Black-throated blue warbler survival in winter in Jamaica (black solid line) is correlated with ENSO variations, as reflected in the Southern Oscillation Index (SOI, gray solid line) (Sillett et al. 2000). These songbirds breed in northeastern United States, including at the HBR in New Hampshire (dashed line). Reprinted with permission from AAAS.

Songbird survival in temperate and tropical forests. Many songbirds in the northeastern United States, including the Hubbard Brook Ecosystem Study LTER site (HBR), breed in temperate latitudes but overwinter in the tropics; thus an understanding of bird dynamics in the tropics is important to sites in the continental United States. Annual survival of the black-throated blue warbler in Jamaica is strongly associated with the Southern Oscillation Index (Sillett et al. 2000). Annual warbler survival estimated from mark-recapture analyses in Jamaica was low during El Niño conditions and high during La Niña (figure 3-4). The mechanism involved appears to be enhanced food availability in Jamaica during the wet winters of La Niña years (Sillett et al. 2000). Although annual survival of breeding warblers in New Hampshire was relatively constant through time (figure 3-4), ENSO affects blue warblers in the breeding season through increased body mass of fledglings during La Niña conditions, which can be associated with higher survival and fecundity of breeding birds (Sillett et al. 2000). The lack of a relationship between survival of birds in New Hampshire and changes in ENSO is probably due to many birds overwintering on islands without a strong climatic effect of ENSO (Sillett et al. 2000).

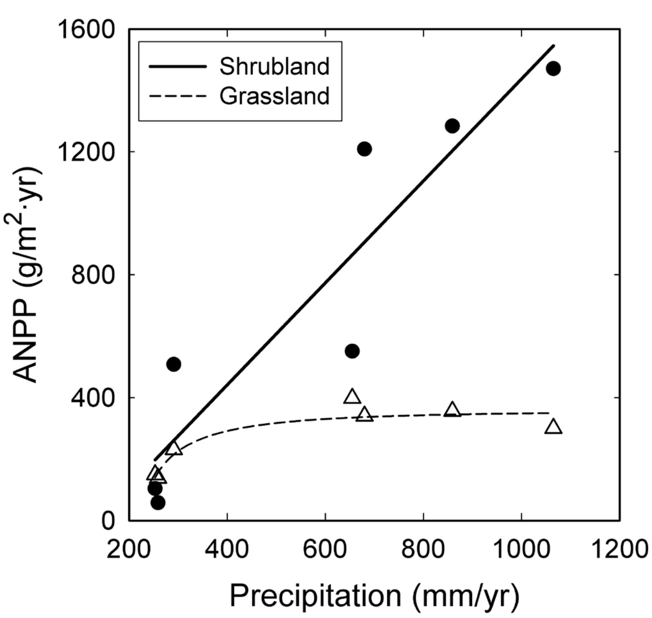

Figure 3-5. Relationship between aboveground annual net primary production (ANPP) and mean annual precipitation for shrublands is linear (solid line) across eight North American sites, including the Arctic (ARC), Jornada (JRN), Konza Prairie Biological Station (KNZ), Sevilleta (SEV), and Virginia Coast Reserve (VCR) sites. The relationship for grasslands (dashed line) peaks near 700 mm/year of precipitation, when nitrogen and light become limiting. (Redrawn from Knapp et al. 2008.)

Hypothesis 2: Gradual, Progressive Climate Change Can Elicit Marked Responses in Ecosystem Structure

Progressive climate change has led to gradual long-term changes in ecologically important aspects of the physical environment at many sites (chapter 11): Water temperatures have increased off the coast of California, ice duration has shortened in lakes in Wisconsin, sea level has risen along both coasts of North America, and streamflow has changed in places as diverse as Michigan, Massachusetts, and Florida. These gradual environmental changes have resulted in directional ecological responses, three of which we will illustrate here.

Shifting shrubland/grassland dominance with altered precipitation. Many ecological systems are highly responsive to climatic variability. Annual above-ground productivity of grassland ecosystems, for example, is related to annual precipitation. In a comparative study across eight grassland sites in North America, including five LTER sites, mean annual precipitation explains much of the variability in above-ground productivity (figure 3-5; Knapp et al. 2008). Across these grassland sites spanning a precipitation gradient from 250 to 1,100 mm/y, productivity increases until a threshold is reached as precipitation approaches 700 mm/y. At larger amounts of precipitation, production is limited by additional resources such as nitrogen and light. In contrast, shrublands show no evidence of saturated productivity over the same range of precipitation.

These results suggest that gradual changes in precipitation at the wet end of the gradient (for example, at KNZ) may have marked consequences for vegetation dominance such that an increase in rainfall would favor woody plant dominance over grasses. Shifts in dominance at the dry end (for example, at JRN) are more likely related to changes in seasonality of precipitation where an increase in winter precipitation would favor shrubs and an increase in summer precipitation would favor grasses (figure 4-1). These shifts in dominance have important consequences for ecosystem services, such as forage production, biodiversity, and air and water quality, that are provided by grasslands or shrublands to human populations.

Decline in pelagic tunicates with ocean warming. Long-term records of ocean temperatures and zooplankton biomass off the coast of California (CCE) have documented a long-term decline in biomass of pelagic tunicates called salps, along with a long-term increase in the temperature of the water column and its density stratification (the vertical density difference between surface and subsurface waters) (figure 3-6). While correlated with changes in temperature, the decline in salp biomass appears to be related to changes in ocean circulation rather than to ocean warming itself (Lavaniegos and Ohman 2007). This decline in biomass has implications for the vertical movement of carbon from the surface to deep ocean waters because salps have very high grazing rates and produce fecal pellets that sediment rapidly out of ocean surface waters. These changes in surface dwelling salps are thought to alter the "biological pump" of carbon into the deep sea: Lower biomass of salps may result in reduced flux of organic carbon to benthic organisms living on the deep sea floor (Smith et al. 2008).

Decline in grasshopper diversity with increased precipitation. An increase in annual precipitation in central Minnesota at the Cedar Creek LTER site (CDR) has been associated with a decline in grasshopper species richness (figure 3-7) (M. Ritchie et al., personal communication). These declines in richness appear to be related to a series of cooler, cloudier, wetter-than-normal summers in the past 15 years. The primary loss of species has been in the band-winged (Oedipodinae) and slant-faced (Gomphocerinae) subfamilies of grasshoppers, which apparently need warmer weather to develop and lay eggs during the relatively short

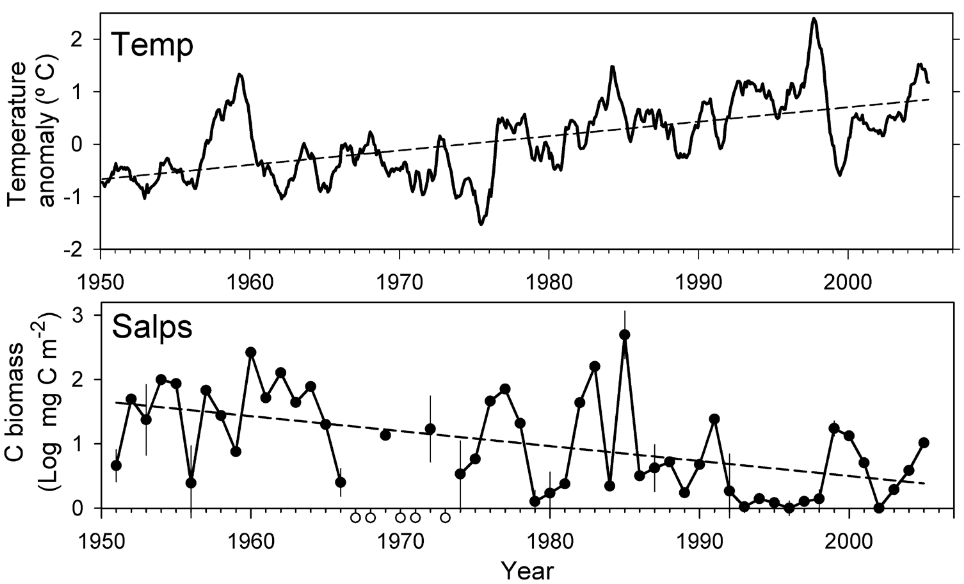

Figure 3-6. Top: Ocean temperature measured at the Scripps pier, California Current Ecosystem (CCE), over the past 5 1/2 decades (anomalies from the seasonal mean). (Data from http://cce.lternet.edu/data/.) Bottom: Decline in carbon (C) biomass of a group of pelagic tunicates known as salps, a zooplankton taxon whose grazing activity and fecal pellet production accelerate vertical transport of organic carbon into the deep sea. (Modified from Lavaniegos and Ohman 2007; data from http://cce.lternet.edu/data/.) Significant regression lines are shown in both panels (dashed lines).

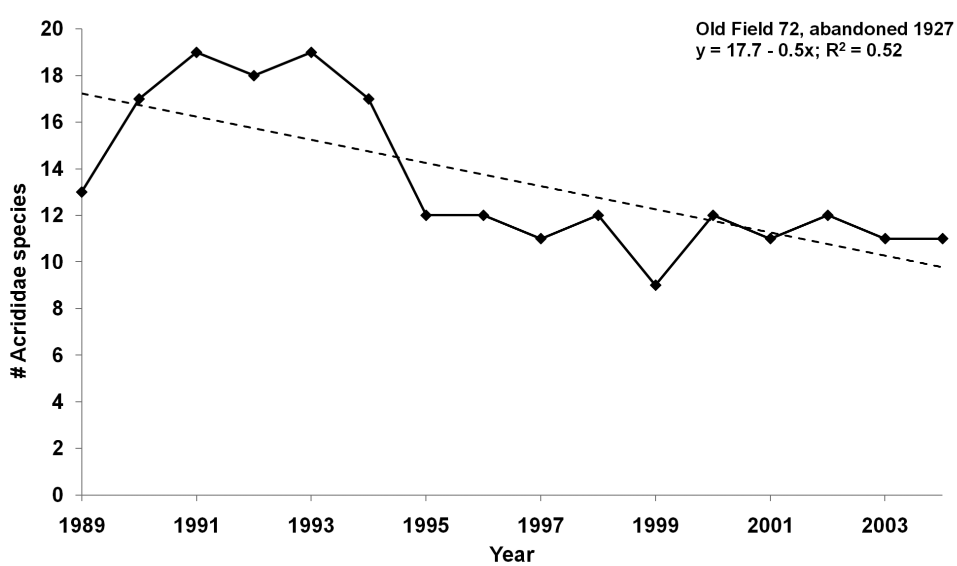

Figure 3-7. Decline of species richness of grasshoppers in the family Acrididae from old field 72 at the Cedar Creek site (CDR) over 15 years (M. Ritchie et al., personal communication). This decline parallels a longer-term increase in precipitation in the region. (Original data from http://www.cedarcreek.umn.edu/. Synthesized data from http://www.ecotrends.info.)

Minnesota summers. Accumulation of litter is also associated with cooler, wetter summers. Shading of the ground by litter may also slow egg development of these groups, leading to declines in their populations (Ritchie 2000).

Conclusions

Our changing climate leaves a footprint on ecological systems that at times may be subtle, but is long lasting. Resolving the climate footprint—a part of Magnuson's (1990) "invisible present"—
requires sustained and standardized observational, experimental, and modeling programs, such as those developed and maintained at LTER and other long-term sites (Greenland et al. 2003). Although climatic drivers are often measured using standardized approaches (Greenland et al. 2003, WMO 2008), ecological responses to climate are more variable in both the types of responses measured (such as plant production and animal abundance) and in the attributes of the variable, such as sampling frequency (daily, weekly, peak growth), spatial scale of the sample unit (square meter, hectare, sweep nets), and taxonomic resolution (species, genera, family, functional group).

Recommendations for future research that would allow cross-site comparisons of ecological responses to climate and other global change drivers are provided in chapter 17. Expanded comparative studies across diverse biomes offer great promise for discerning characteristics of the climate footprint. These studies can also be used to tease out cause and effect relationships that are fundamental to developing the capacity for forecasting future trajectories of coupled human-natural ecosystems under different climate change scenarios.

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Chapter 4

Cross-Site Comparisons of State-Change Dynamics

D.P.C. Peters, W.R. Fraser, T.K. Kratz, M.D. Ohman, A. Rassweiler, S.J. Holbrook, and R.J. Schmitt

Changes in the state of a system—for example from grassland to shrubland or from dominance by one fish species to another species—with associated changes in other parts of the system, are often irreversible. These state changes are related to changing climatic conditions (chapter 11) interacting with human activities (MEA 2005b). State changes can lead to positive effects on ecosystems; but more frequently, such as with the invasion by an exotic species, the changes are negative and result in altered levels of biodiversity, shifts in rates of nutrient cycling, changes in air and water quality, and increased losses of soil and nutrients to wind and water erosion (Scheffer et al. 2001, Scheffer and Carpenter 2003).

Examination of the dynamics of state changes across a variety of ecological systems can identify common interactions among patterns and processes that can provide new insight into the drivers of these dynamics (Bestelmeyer et al. 2011). It is only through the use of long-term data that we can identify persistent changes in states, the drivers influencing these shifts, and potential reversals or modifications of shifts through time.

Here we illustrate common features of state changes for six systems with a diverse set of organisms (plankton, invertebrates, fish, plants, or penguins).

Vegetation state changes in deserts. In the American Southwest and throughout arid systems globally, large areas of land have converted from perennial grassland to shrubland over the past several centuries (Reynolds and Stafford Smith 2002). This state change is self-reinforcing as positive feedbacks between shrubs and soil properties allow continued shrub survival and promote grass mortality (Schlesinger et al. 1990, Rietkerk et al. 2004). The result is a discontinuous cover of shrubs and unvegetated areas that increases movement of soil and nutrients from bare areas to beneath shrub canopies. In arid systems where average annual precipitation is typically less than 300 mm, one consequence of this shift from grassland to shrubland is a reduction in above-ground net primary production (figure 3-5).

Although this process of desertification has been well studied (MEA 2005a), little is known about the conditions which affect rate and pattern of shrub dominance or variation in grass survival at patch to landscape scales (Peters et al. 2006). Researchers at the Jornada ARS/LTER (JRN) and Sevilleta LTER (SEV) sites have documented this shift using long-term observations (figure 4-1) and are using experimental manipulations to test the importance of biotic and abiotic processes to threshold behavior through time and across space (Peters et al. 2004, 2009).

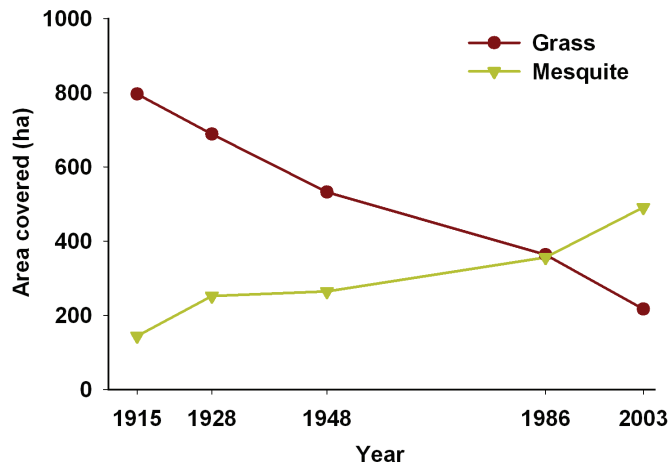

Figure 4-1. State change from grassland (brown) to mesquite shrubland (green) in the Chihuahuan Desert based on changes in area of each ecosystem type through time (Peters et al. 2004). Reprinted with permission from the National Academy of Sciences, USA.

Penguin dynamics in Antarctica. Along the rapidly warming western Antarctic Peninsula (Vaughan et al. 2003), southward climate migration is driving replacement of Adélie penguins by Gentoo and Chinstrap penguins (Ducklow et al. 2007, McClintock et al. 2008). Adélie penguins are a true polar species, with a life history that is critically dependent on the availability of sea ice, especially during winter (Fraser et al. 1992, Ainley 2002). In contrast, the other two species originate in sub-Antarctic latitudes and are ice-intolerant (Fraser et al. 1992, Williams 1995). The population trends shown in figure 4-2 are unprecedented, with the paleo-record indicating that neither Gentoo nor Chinstrap penguins have occupied the region over the past 700 years (Emslie et al. 1998). The changes in penguin abundance and species

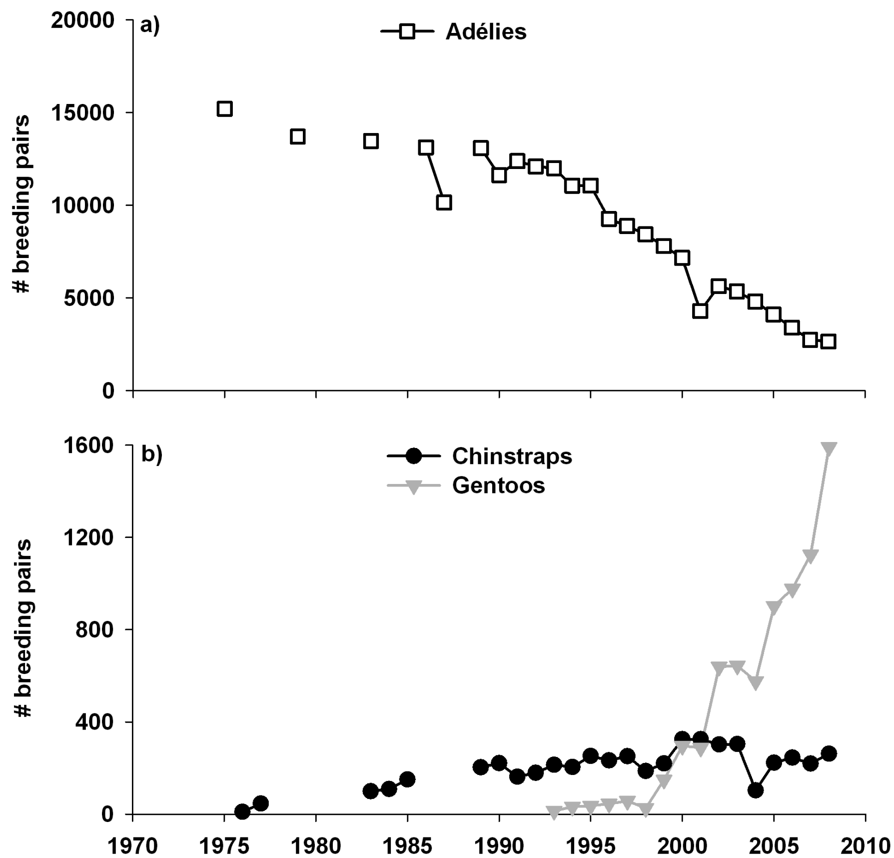

Figure 4-2. State change based on number of breeding pairs of birds from dominance by (a) Adélie penguins, a polar species, to (b) dominance by the ice-intolerant Gentoo and Chinstrap penguins in Antarctica. (Updated from McClintock et al. 2008.)

composition near Palmer Station LTER (PAL) reflect a reduction in the extent and duration of sea ice cover in the area (Ducklow et al. 2007), which is related to the positive Southern Oscillation Index during warm El Niño conditions (figure 3-1).

Fish dynamics in Wisconsin lakes. Similar state changes have been observed in lakes in Wisconsin (figure 4-3). The non-native rainbow smelt became established in Sparkling Lake in the mid 1980s and caused major changes in the lake's fish community (Hrabik et al. 1998, Wilson and Hrabik 2006). Cisco were extirpated by smelt predation on juveniles. Yellow perch also have been greatly reduced because young-of-year smelt out-compete young-of-year yellow perch for prey. Recent declines in rainbow smelt catch per unit effort may be attributed to a harvesting program intended to reduce abundance of this harmful non-native species. It is unclear whether these changes are irreversible. Scientists from the North Temperate Lakes LTER (NTL) are conducting a decade-long experiment that combines manual harvesting of smelt with enhanced stocking and regulatory protection of its predators to reduce smelt to low numbers or possibly remove them from the lake. It is unclear whether the abundance of cisco (if reintroduced) or yellow perch will increase when smelt abundance is experimentally reduced.

Plankton dynamics in the Pacific Ocean. Along the coast of southern California, variations in plankton populations are closely linked to long-term changes in physical conditions in the ocean environment. A

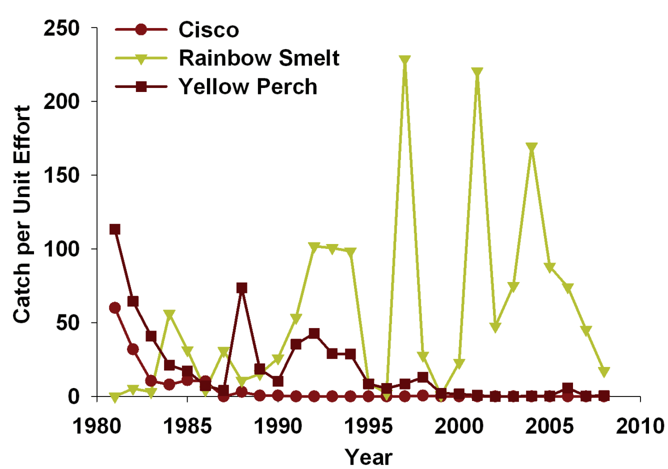

Figure 4-3. State change in lakes in Wisconsin based on fish catch data from dominance by native cisco and yellow perch to dominance by the introduced rainbow smelt. (Updated from Hrabik et al. 1998, Wilson and Hrabik 2006.)

relatively abrupt change occurred in the mid 1970s in sea surface temperature (figure 3-6) (reflected by the Pacific Decadal Oscillation (PDO) index in figure 4-4), with accompanying changes in several members of the plankton assemblage. For example, a subtropical species of krill *(Nyctiphanes simplex)* increased in abundance in the mid 1970s (figure 4-4). Other types of suspension-feeding zooplankton known as salps, one group of which typically enters the study area from higher latitudes, decreased abruptly in biomass at this time (Ohman and Venrick 2003). Following the major El Niño of 1997-98, there was a decrease in sea surface temperatures in the northeastern Pacific Ocean with accompanying reversals of the changes in some plankton populations.

The nodal points of these ecosystem transitions are associated with changes in ocean circulation, but the persistence of the altered communities for two to three decades at a time appears to be related to biotic responses. Whether these ecosystem changes represent cyclical variations is under investigation by the California Current Ecosystem LTER (CCE) site.

Subtidal dynamics off the Pacific Coast. Rocky reefs are known to exhibit sudden changes in state in which one type of benthic community is replaced by another. Scientists at the Santa Barbara Coastal LTER (SBC) have documented a particularly dramatic example of this shift on shallow subtidal reefs at Santa Cruz Island: The density of a small filter-feeding sea

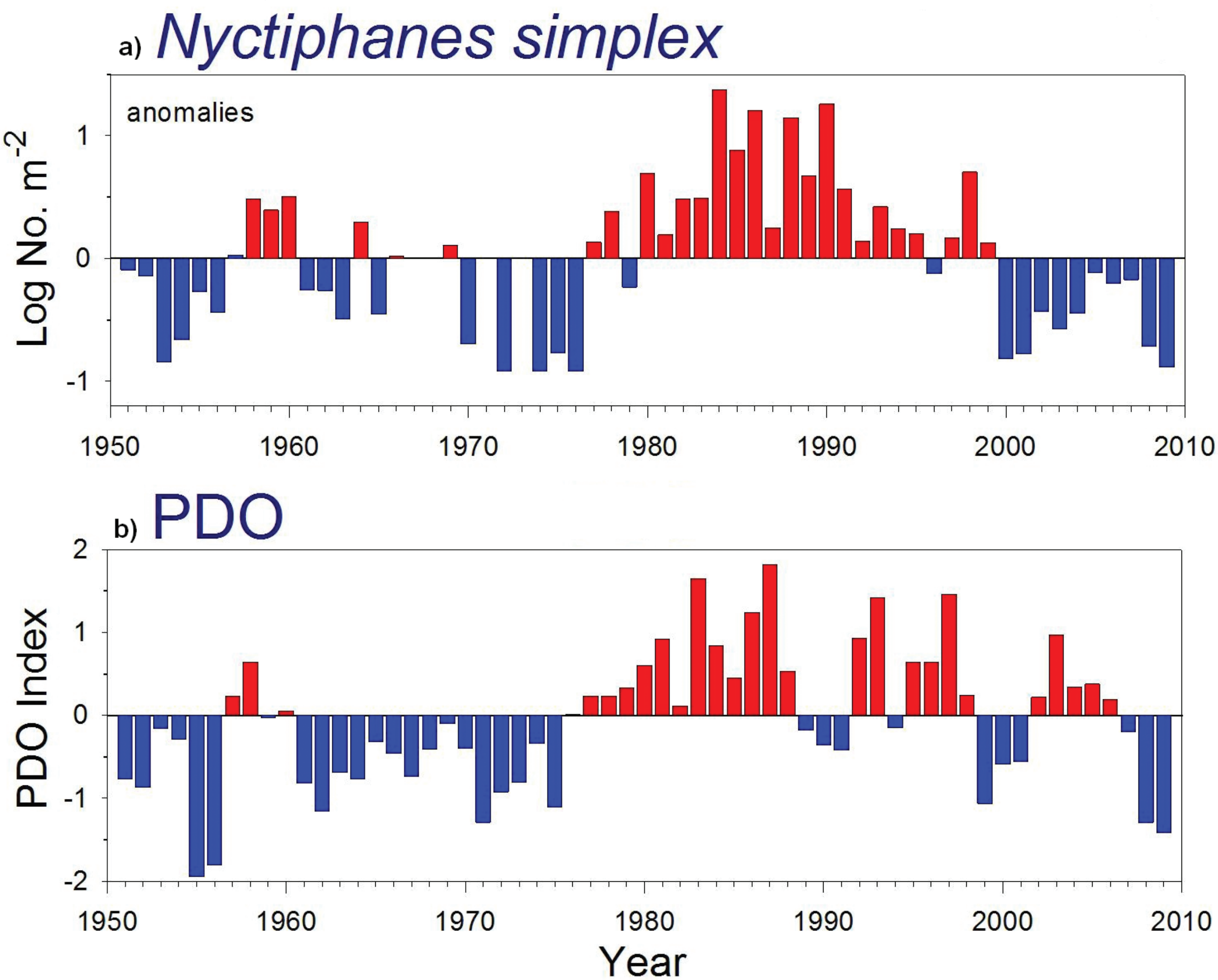

Figure 4-4. Long-term variability in the northeastern Pacific Ocean off the coast of southern California: (a) anomalies of springtime abundance of the euphausiid *Nyctiphanes simplex* and (b) annual averages of the Pacific Decadal Oscillation (PDO) index. (M. Ohman, updated from Brinton and Townsend 2003.)

cucumber, *Pachythyone rubra,* increased from near zero to thousands per square meter (figure 4-5). This change occurred within 2 years and resulted in *P. rubra* covering more than 90 percent of the bottom at many sites (Rassweiler 2008). Manipulative experiments show that *P. rubra* competes for space with understory macroalgae, which had dominated these sites prior to the increase in sea cucumber density. For more than a decade, macroalgae were unable to recover at these sites, in part because sea cucumbers consume algal spores in the water column.

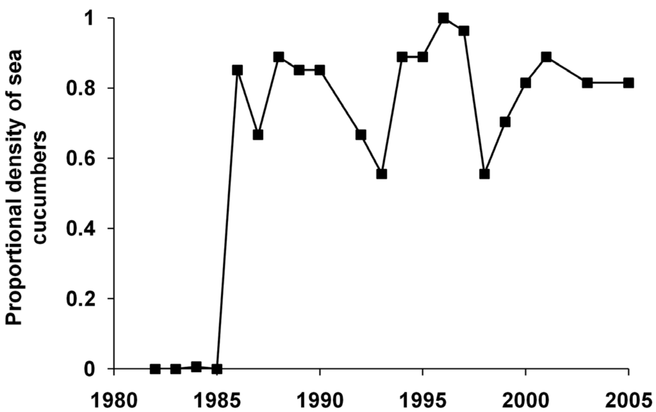

Figure 4-5. State changes in subtidal reefs off the coast of southern California. Sea cucumber biomass increasing over time. (Redrawn from Rassweiler 2008.)

Once the filter feeders reach a high enough abundance, they can reduce settlement rates of macroalgal spores to levels that are low enough to prevent reestablishment of macroalgae. Shifts from an algal-dominated state to one dominated by invertebrate filter feeders represents a major change in the trophic structure of the benthic food web, as energy is derived from captured plankton instead of from primary production by macroalgae. The decline in macroalgae has reduced the abundance of a wide variety of organisms that use the algae for food and shelter, including small crustaceans, which are a key food resource for many reef fishes.

Shifts in coastal fish assemblages in the Pacific Ocean. Similar to the dynamics of plankton along the coast of southern California, communities of rocky reef organisms in the same region underwent dramatic changes in response to the abrupt shift from the cool phase to the warm phase of the PDO in the mid 1970s. This climate shift brought warmer, nutrient-poor surface waters to nearshore regions, as well as increases in the intensity and frequency of El Niño Southern Oscillation episodes. Composition of reef fish assemblages changed in response to this abrupt shift in physical conditions of the nearshore ocean environment. For example, at coastal sites near Los Angeles, CA, dominance of the assemblage shifted from cold-affinity, northern species to warm-affinity, southern species following the abrupt warming of surface waters (figure 4-6). In addition, by the mid 1990s abundance of nearly all fish species had declined by an average of 69 percent (Holbrook et al. 1997, Brooks et al. 2002).

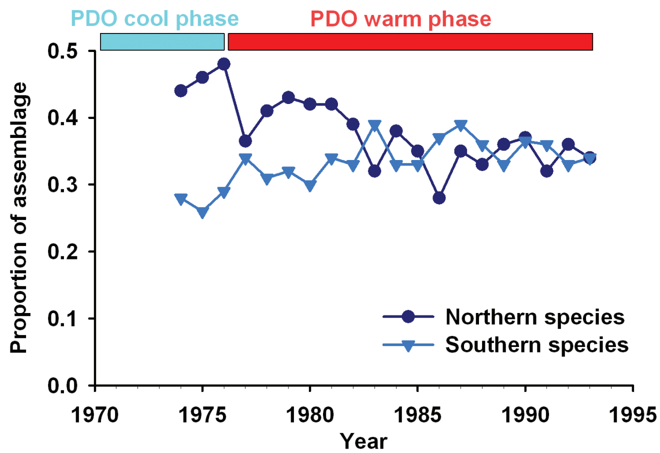

Figure 4-6. Temporal patterns in composition of the fish assemblage on reefs in the Southern California Bight. Shown are the proportions of the annual total species present that were northern species (cold water affinity: circles) and southern species (warm water: triangles). (Redrawn from Holbrook et al. 1997.)

The lower productivity of the coastal marine ecosystem was also accompanied by large effects on population abundance and reef trophic structure. At the SBC study sites on Santa Cruz Island, CA, declines of a similar magnitude were observed for several linked trophic levels in a model food web (several species of surfperches [Pisces: Embiotocidae], the standing stock of their crustacean prey, and the biomass of understory macroalgae on which the prey reside) (Holbrook and Schmitt 1996, Holbrook et al. 1997). The SBC is exploring whether observed changes in composition of the fish assemblage and in trophic structure of the community represent reversible phases driven by cyclical climatic variation.

Conclusions

These examples clearly show the effect of global environmental change (warming, invasive species, altered trophic structure) on the abundance and distribution of dominant and subordinate species in aquatic, marine, and terrestrial systems. In many cases, environmental drivers have shifted to the point that current conditions are leading to threshold changes in species abundance within communities and are altering species range distributions both regionally and globally. However, this era of rapid environmental change is only beginning to be manifested in species responses. Thus, researchers will continue to need long-term data to quantify and predict the nonlinear system responses expected in the future.

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Chapter 5

Patterns of Net Primary Production Across Sites

A.K. Knapp, M.D. Smith, D.P.C. Peters, and S.L. Collins

Net primary production (NPP) is a fundamentally important and commonly measured ecosystem process that provides an integrative estimate of energy capture and flow into systems and consequently of the energy available for use by other trophic levels. A wide range of productivity levels occurs globally (figure 5-1) with high temporal dynamics among sites (chapter 14). In this brief overview, we discuss approaches to estimating NPP, highlight site-specific trends in productivity, and provide examples of past synthetic analyses across space and time. We focus on aboveground components of NPP for reasons explained below.

Methods of Measuring and Estimating NPP

In terrestrial ecosystems, NPP includes both aboveground (ANPP) and belowground (BNPP) components. Data and analyses are much more common for ANPP because measuring belowground components is technically difficult (Fahey and Knapp 2007). In general, ANPP in terrestrial systems can be directly measured via destructive harvest or estimated with nondestructive (for example, allometric) techniques. Data in this book include both approaches and, because the units of NPP are usually grams of dry mass (or carbon) per unit area per unit time (usually per year), comparisons across ecosystems are facilitated. In addition to the challenges associated with measuring BNPP, estimating ANPP in forests and NPP in aquatic systems often require techniques that use much different spatial and temporal scales than what is employed in ecosystems dominated by herbaceous plants. For a recent review of the most commonly used and accepted methods of estimating both ANPP and BNPP, see Fahey and Knapp (2007).

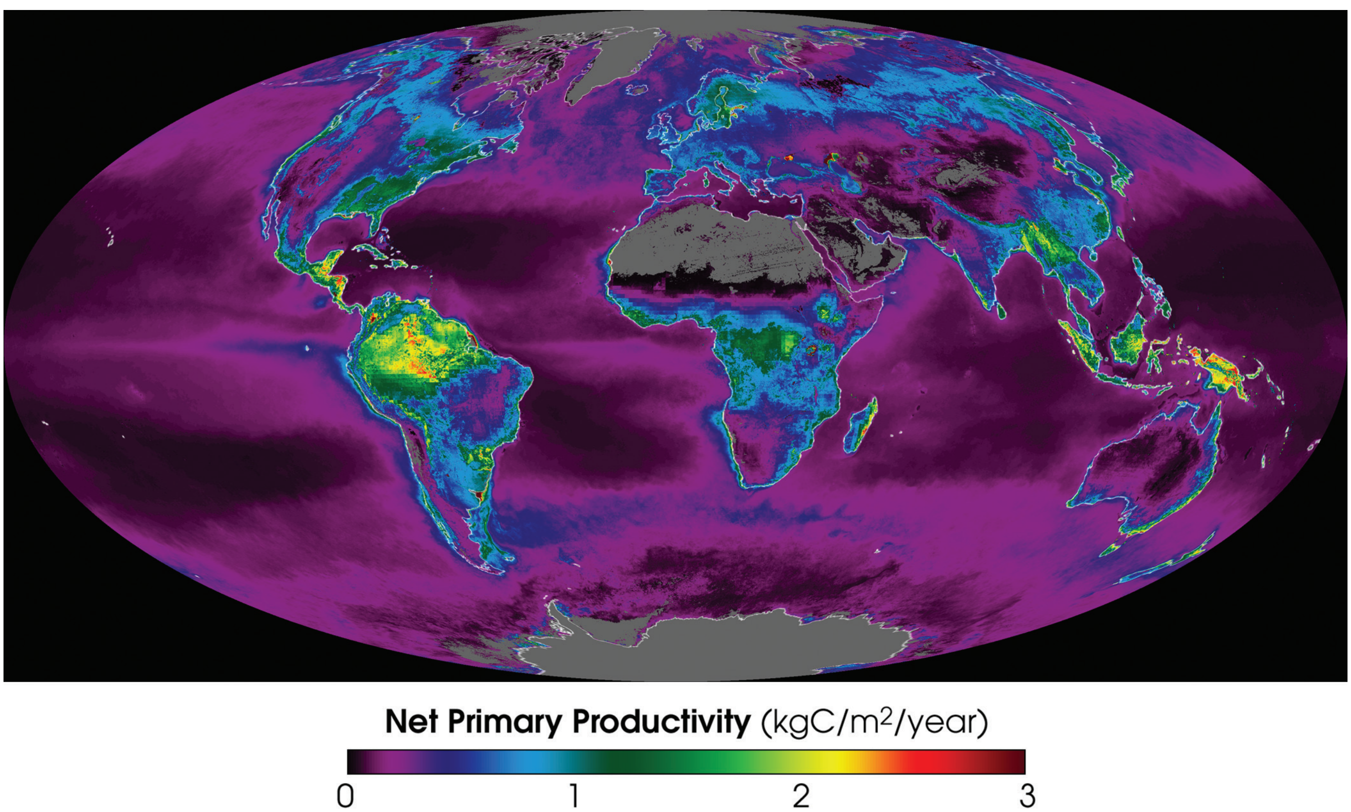

Figure 5-1. Global patterns in annual average net primary production on land and in the ocean in 2002. The yellow and red areas show the highest rates, 2 to 3 kilograms of carbon per square meter per year. The green, blue, and purple shades show progressively lower productivity. (Map from NASA Goddard Space Flight Center, http://science.hq.nasa.gov/oceans/system/climate.html.)

Temporal and Spatial Trends in ANPP

For many sites, both increasing and decreasing trends in ANPP are evident over time (figures 14-1 to 14-4) and are often a consequence of disturbance regimes or changes in plant community composition. In many sites, spatial variation among locations within a site can overwhelm temporal variation (figure 5-2). However, strong interannual variation in ANPP over time is not always the rule; instead, trends in ANPP (either positive or negative) can be quite consistent from year to year (figure 5-3). Additional trends in ANPP, surrogates for NPP, and aquatic productivity are included in chapter 14.

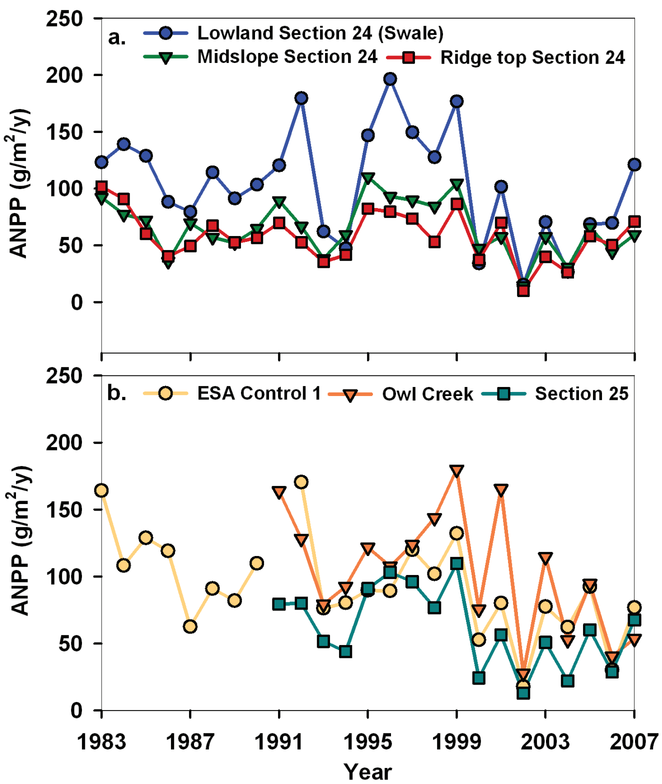

Figure 5-2. Patterns of aboveground net primary production (ANPP) for the Shortgrass Steppe (SGS) from 1983 to 2007 for 6 locations based on topographic position and soil texture from high sand (Owl Creek) to low sand (Pasture 25). (Original data from http://sgs.cnr.colostate.edu/; synthesized data from http://www.ecotrends.info.)

Cross-Site Synthetic Analyses

One of the advantages of the EcoTrends database is that it facilitates more comprehensive synthetic analyses of NPP data across space and time. The determinants of differences among sites in NPP quantity and dynamics have long been of interest to ecologists (Rosenweig 1968, Webb et al. 1978). More recent analyses have

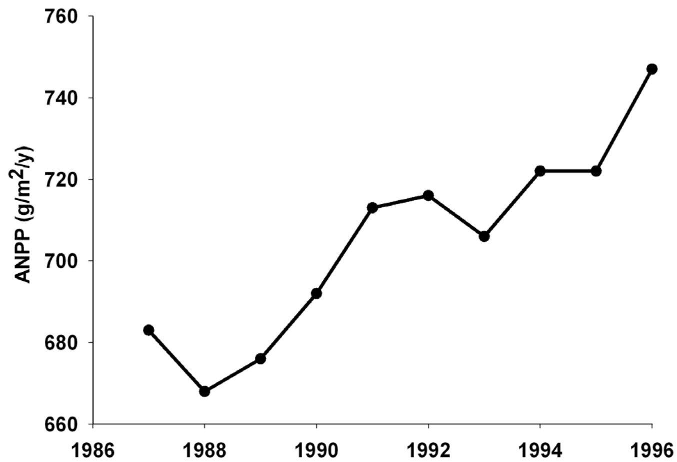

Figure 5-3. Pattern of aboveground net primary production (ANPP) for a mixed deciduous forest site at the Hubbard Brook Ecosystem Study (HBR) site from 1987 to 1996. (Original data from http://intranet.lternet.edu/cgi-bin/anpp.pl; synthesized data from http://www.ecotrends.info.)

begun to take advantage of long-term data across sites (Knapp and Smith 2001, Huxman et al. 2004). These analyses have provided key insights into the relative roles of biotic versus abiotic drivers of dynamics as well as elucidating where and when biogeochemical versus climatic factors underlie patterns of NPP across biomes. For example, the strong role that precipitation plays in determining ANPP across grassland sites is clearly evident in a multisite analysis (figure 5-4) (Muldavin et al. 2008). Across a broader range of terrestrial ecosystems, differential sensitivity to mean annual precipitation appears with other limitations (temperature or biogeochemistry) becoming more important in more mesic and productive ecosystems (figure 5-5) (Huxman et al. 2004).

Biotic constraints on ANPP, such as vegetation composition or meristem limitation, can also explain patterns across sites. Lauenroth and Sala (1992) pointed out a space versus time discrepancy when comparing the temporal relationship between ANPP and precipitation at an individual site compared with the same relationship based on ANPP and precipitation across sites (spatial vs. temporal trends, figure 5-6). The shallower slope of the relationship at any one site reflects site-specific vegetation constraints on the capability of the ecosystem to respond to changes in precipitation. A similar pattern can be seen for a broader range of sites (figure 5-5). Shifts in plant species composition within a site, due to woody plant encroachment or invasion of shrubs into grasslands, can dramatically change ANPP at that site (with no change in environmental conditions) as well as alter patterns of ANPP across sites (Knapp et al. 2008).

Another manifestation of how vegetation structure can influence ANPP responses to changes in precipitation was demonstrated by Knapp and Smith (2001) in a multisite synthetic analysis of long-term ANPP data. The interaction between meristem density (low in xeric ecosystems and high in mesic ecosystems) and interannual variability in precipitation (high in xeric ecosystems and low in mesic ecosystems) resulted in a pattern where the greatest interannual variability in ANPP (CV in figure 5-7) was in grasslands.

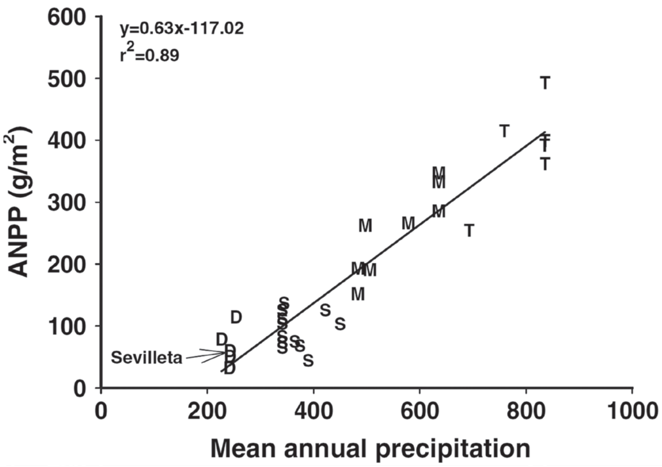

Figure 5-4. Regional comparison of aboveground net primary production (ANPP) and long-term mean annual precipitation for four grassland types: D = desert grassland, S = shortgrass steppe, M = mixedgrass prairie, T = tallgrass prairie (Muldavin et al. 2008). The Sevilleta site is identified. Reprinted with permission from Springer Science+Business Media.

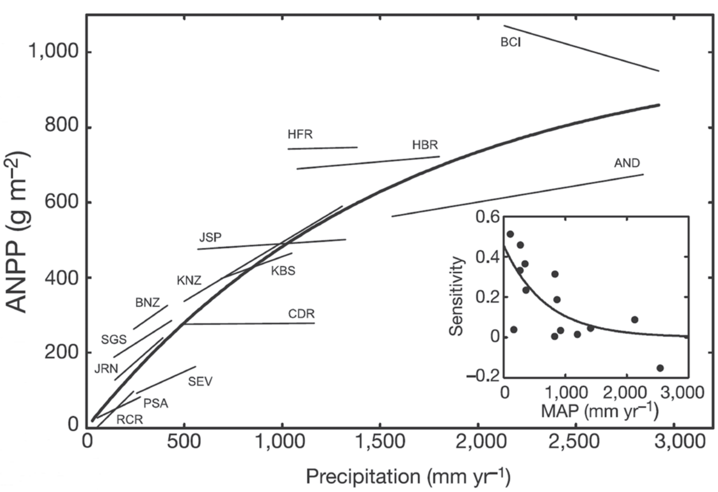

Figure 5-5. Between-year variation in aboveground net primary production (ANPP) across a precipitation gradient for 14 sites. Site-specific relationships developed using linear regression (Huxman et al. 2004). The overall relationship (bold line) shown for all sites: ANPP = 1011.7 x (1 – exp[-0.0006 x PPT]); r^2 = 0.77; P < 0.001. Inset shows site-level slopes of ANPP versus annual precipitation as a function of mean annual precipitation (MAP). Reprinted with permission from Macmillan Publishers Ltd.

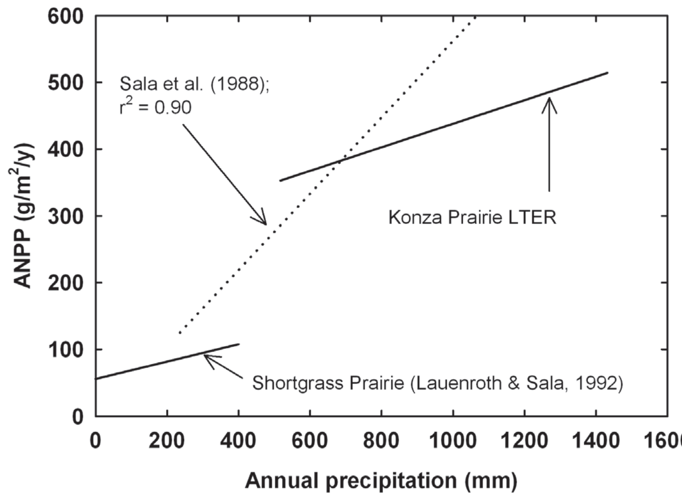

Figure 5-6. Aboveground net primary production (ANPP) has a different relationship with mean annual precipitation for sites located across a rainfall gradient (dashed line) compared with the relationship between ANPP and precipitation in each year for two sites (solid lines): the Shortgrass Steppe (SGS) site (Sala et al. 1988, Lauenroth and Sala 1992) and the Konza Prairie Biological Station (KNZ) site (Knapp et al. 1998). Reprinted with permission from Oxford University Press, Inc.

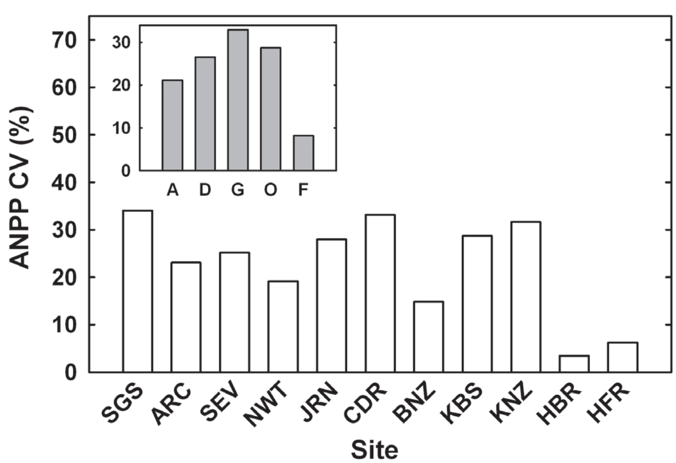

Figure 5-7. Comparison of the temporal coefficient of variation (CV) in aboveground net primary production (ANPP) for 11 sites. Inset shows CV data combined by biome type: A = arctic and alpine sites, D = desert sites, G = grassland sites, O = old fields, F = forest sites (Knapp and Smith 2001). Reprinted with permission from AAAS.

Future Analyses

In a changing world where both global and local changes in climate and nutrient deposition are affecting resources that influence NPP (chapters 11, 12), a re-assessment of past studies and assumptions is warranted, and many questions remain to be addressed (Smith et al. 2009):

- How do the dynamics and amplitude of change in NPP vary across a broad range of ecosystems?
- What are the key drivers of NPP change and dynamics? Is there convergence among ecosystems to a few key drivers?
- How can we more directly compare patterns and controls of NPP in terrestrial and aquatic systems?
- How do ecosystems vary in their sensitivity to their drivers, and is there predictive value in this sensitivity?

Conclusions

Understanding patterns and controls of NPP have been a long-standing challenge for ecological research. This challenge remains a core research area for many sites. As the number of comparable long-term datasets across ecosystems grows, answers to these and other key questions about NPP will be possible in the future.

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Chapter 6

Cross-Site Comparisons of Precipitation and Surface Water Chemistry

C.T. Driscoll, P.M. Groffman, J.M. Blair, A.E. Lugo, C.M. Laney, and D.P.C. Peters

The biogeochemistry of ecosystems involves the transport or cycling of elements (such as sulfur, carbon, nitrogen, calcium) and compounds (such as water) through the biotic (plants, animals, microbes) and abiotic (soils, atmosphere) components. All elements and compounds cycle through the Earth's system, although at different rates and by different pathways that depend on their chemical characteristics and the extent to which they are utilized by organisms.

Cycling involves both inputs to and losses from different pools or standing stocks and the transformations of major and trace elements (figure 6-1). Inputs include weathering from rocks and minerals and deposition from the atmosphere (wet in precipitation and dry as gases or particles). Losses can occur either through gaseous emissions to the atmosphere or drainage below the soil surface or from land to ocean. Pools include the accumulation of elements in the soil, sediments, and vegetation of an ecosystem. Important internal transformations of elements include litter inputs, mineralization of organic matter, uptake of nutrients by vegetation, and the retention or release of material in soil or sediments.

Ecologists measure these pools and fluxes to learn critical information about the functioning of ecosystems. Because the time for a molecule to be completely transported through an ecosystem may be decades to millennia, long-term data provide one of the few means to estimate how ecosystems use and respond to changes in inputs of nutrients and toxic substances. Long-term data can characterize the average size and variability in ecosystem pools and the rates of flow among pools. Monitoring biogeochemical indicators provides useful insights on the response of ecosystems to chronic change, such as in climate or land use, the introduction of invasive species, or changes in air pollution, and short-term disturbances such as fire or climatic events including hurricanes, ice storms, and droughts. Many important ecosystem services, such as the supply of clean air and water, ecosystem productivity, and carbon sequestration, are closely coupled to the biogeochemistry of ecosystems.

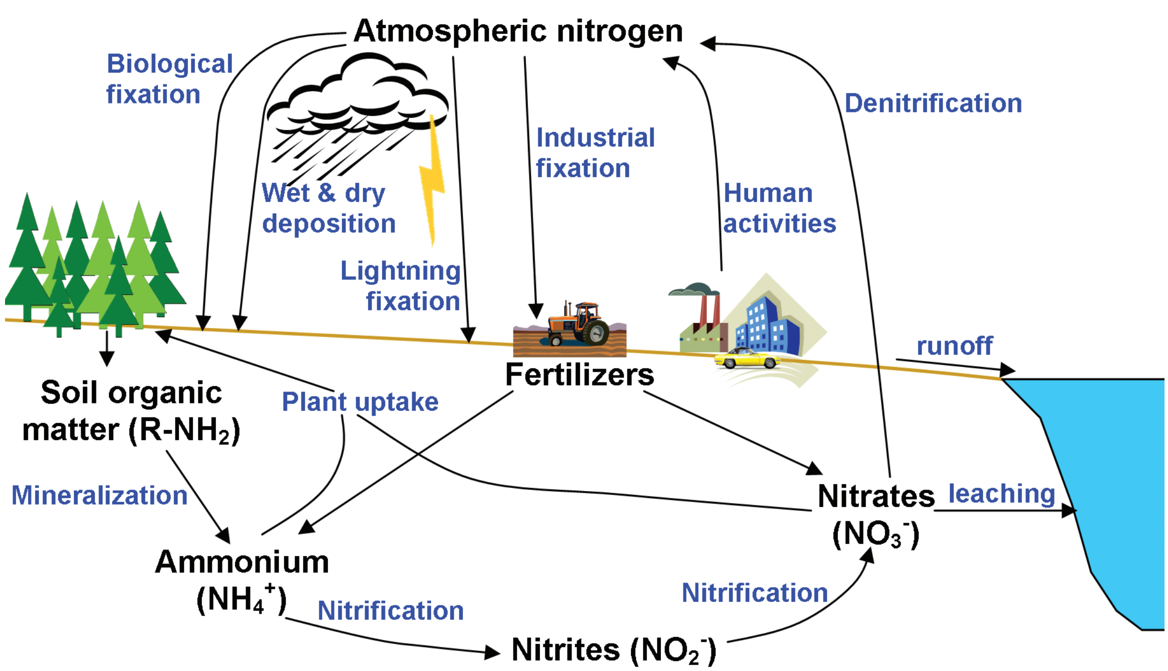

Figure 6-1. Nitrogen cycling through the Earth system involves inputs for wet deposition (in rainfall) and dry deposition (in dust particles and gases), as well as direct human activities such as application of fertilizer. Inputs to the atmosphere come from fossil fuel emissions and gaseous emissions from the soil. Nitrogen also can be exported from land to water bodies through leaching, deep drainage, and runoff. Nitrogen is a major nutrient for plants, animals, and microbes.

Over the past 150 years, marked changes have occurred in atmospheric emissions from human sources and deposition in precipitation across the United States (chapter 12). These changes have been driven by industrialization, human population increases, land-use change, and since the early 1970s, Federal Government controls on industrial and vehicle emissions. Air pollution through atmospheric deposition can influence ecosystem structure and in turn alter ecosystem functioning and services. Atmospheric deposition influences terrestrial ecosystems—including soil chemistry, vegetation nutrient cycling, and species health and distribution—and aquatic ecosystems—including surface water chemistry (chapter 12) and aquatic productivity, density, and composition (chapter 14).

A number of interesting and society-relevant hypotheses can be tested using long-term biogeochemistry data collected from a number of sites located in different ecosystem types and climatic regimes. In this chapter, we use data from chapter 12 to test two hypotheses related to patterns in biogeochemistry across EcoTrends sites and elements:

- Patterns in atmospheric deposition over the past 20 years are different for the eastern and western parts of the United States.
- Changes in atmospheric deposition are related to changes in human population density for some sites.

We test these hypotheses using chemical measurements in wet deposition (nitrate, ammonia, sulfate). To help interpret the patterns and trends in precipitation chemistry, we used sulfur dioxide, nitrogen oxide, and ammonia emission data compiled by the U.S. Environmental Protection Agency (EPA) (www.epa.gov/air/data/geosel.html).

Hypothesis 1. Patterns in Atmospheric Deposition Over the Past 20 Years Are Different for the Eastern and Western United States

In support of our hypothesis, total sulfur dioxide and nitrogen oxide emissions were higher through time for the region of the United States east of the Mississippi River than in the western region (figure 6-2). These patterns are consistent with higher population density on average in the eastern than the western parts of the country (figure 8-1, chapter 13). Emissions of sulfur dioxide are largely associated with coal-fired electric utilities located in the East (Dennis et al. 2007) that contribute sulfate to precipitation. Emissions of nitrogen oxides are largely due to a combination of electric utilities and transportation sources, resulting in nitrate in precipitation. Ammonia emissions are higher in the West than in the East, and are largely associated with agricultural activities (Driscoll et al. 2003).

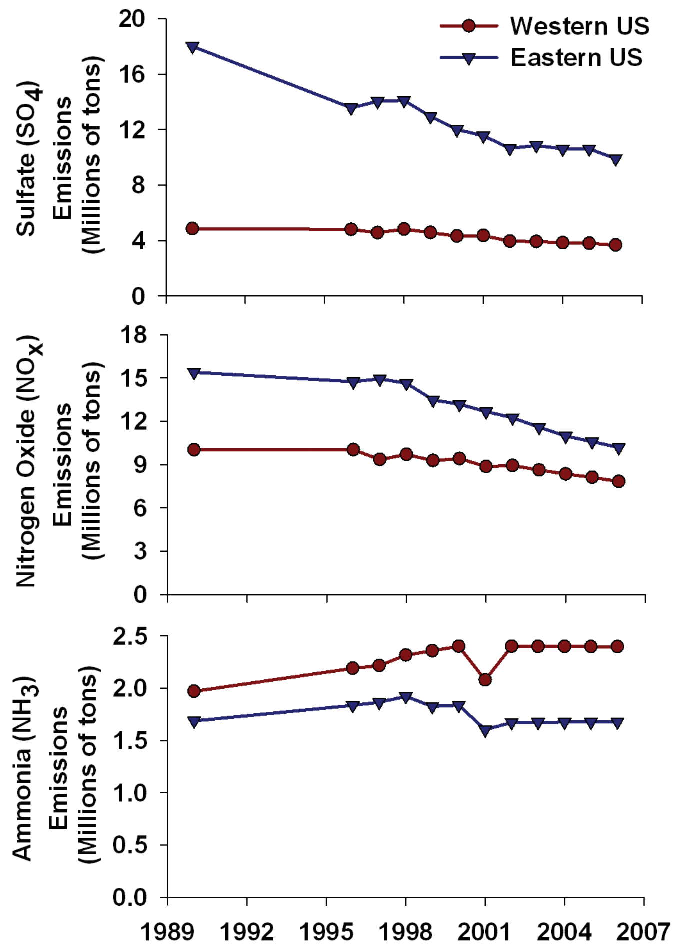

Figure 6-2. Annual atmospheric emissions of sulfur dioxide, nitrogen oxides, and ammonia for the eastern (east of the Mississippi River) and western States from 1990 to 2006 (www.epa.gov/air/data/geosel.html).

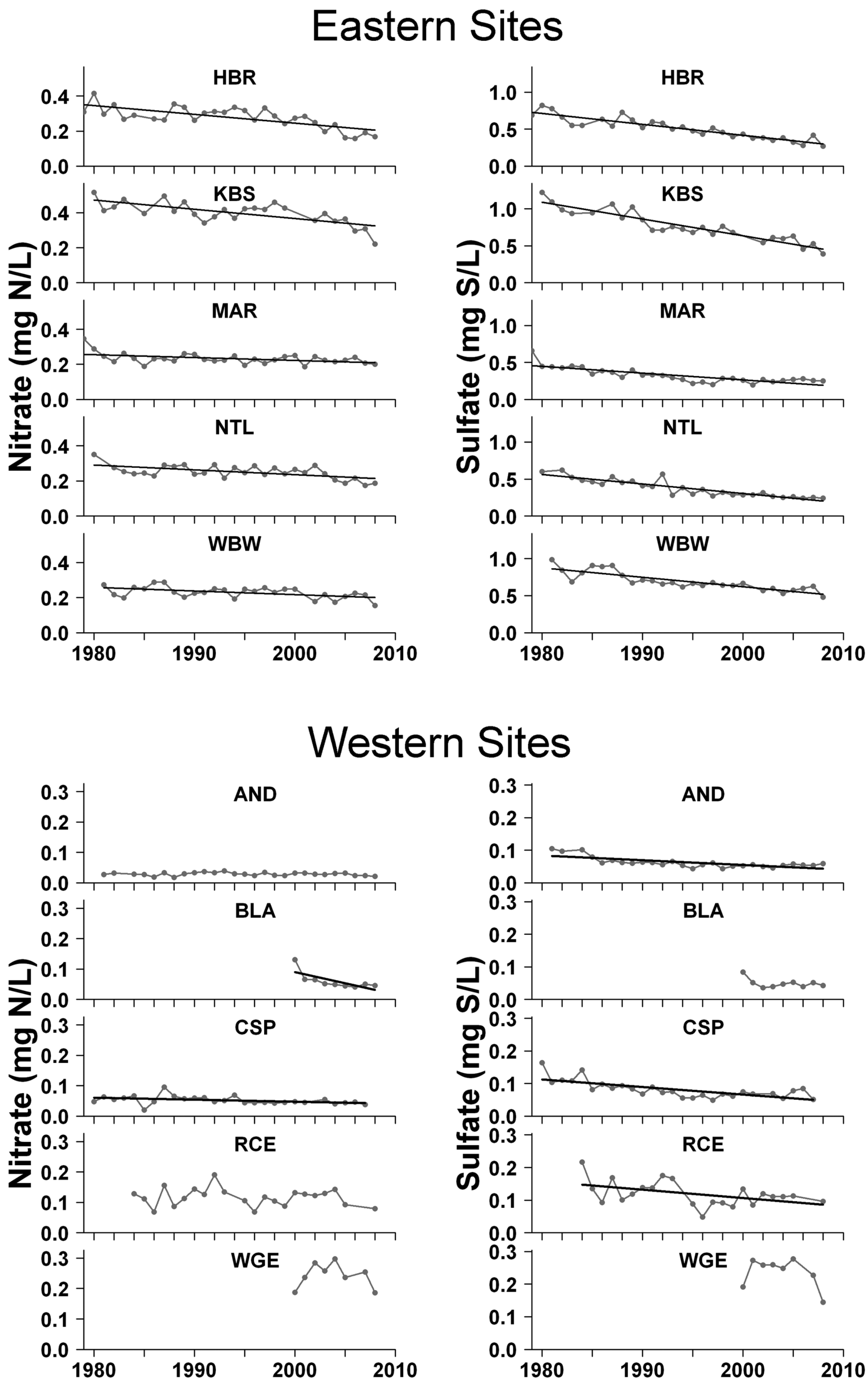

Figure 6-3. Change in annual volume-weighted concentration of nitrate and sulfate in precipitation at five eastern (upper panel: HBR, KBS, MAR, NTL, WBW) and five western sites (lower panel: AND, BLA, CSP, RCE, WGE). (Original data from Internet home pages—see table 1-1—and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.)

The temporal trends in sulfate and nitrate concentrations in precipitation also reflect emission trends regionally. In the East, considerable effort has been made to control sulfur dioxide and nitrogen oxide emissions from electric utilities through the 1990 Amendments of the Clean Air Act and the Nitrogen Oxide Budget Trading Program (Dennis et. al. 2007). These control efforts have resulted in significant decreases in sulfate and nitrate concentrations in precipitation in eastern EcoTrends sites in both forests (HBR, MAR, NTL, WBW) and grasslands (KBS) (figure 6-3, top). In contrast, emissions of nitrogen oxides and sulfur dioxide in the West are either decreasing at a lower rate or not changing (figure 6-2). This limited change in trends through time is reflected by patterns in nitrate concentrations in precipitation for several forest (AND, BLA, CSP) and aridland (RCE, WGE) sites in the West (figure 6-3, bottom). These patterns are likely associated with increasing human development and associated transportation emissions, as well as less aggressive emission controls in the West than in the East.

In general, ammonia emissions have not changed appreciably for either region (figure 6-2) as a result of limited changes in agricultural activities. These trends in nitrogen emissions suggest a pattern of increasing importance of ammonium in the future as a percentage of total atmospheric nitrogen deposition if nitrogen oxide emissions continue to decrease.

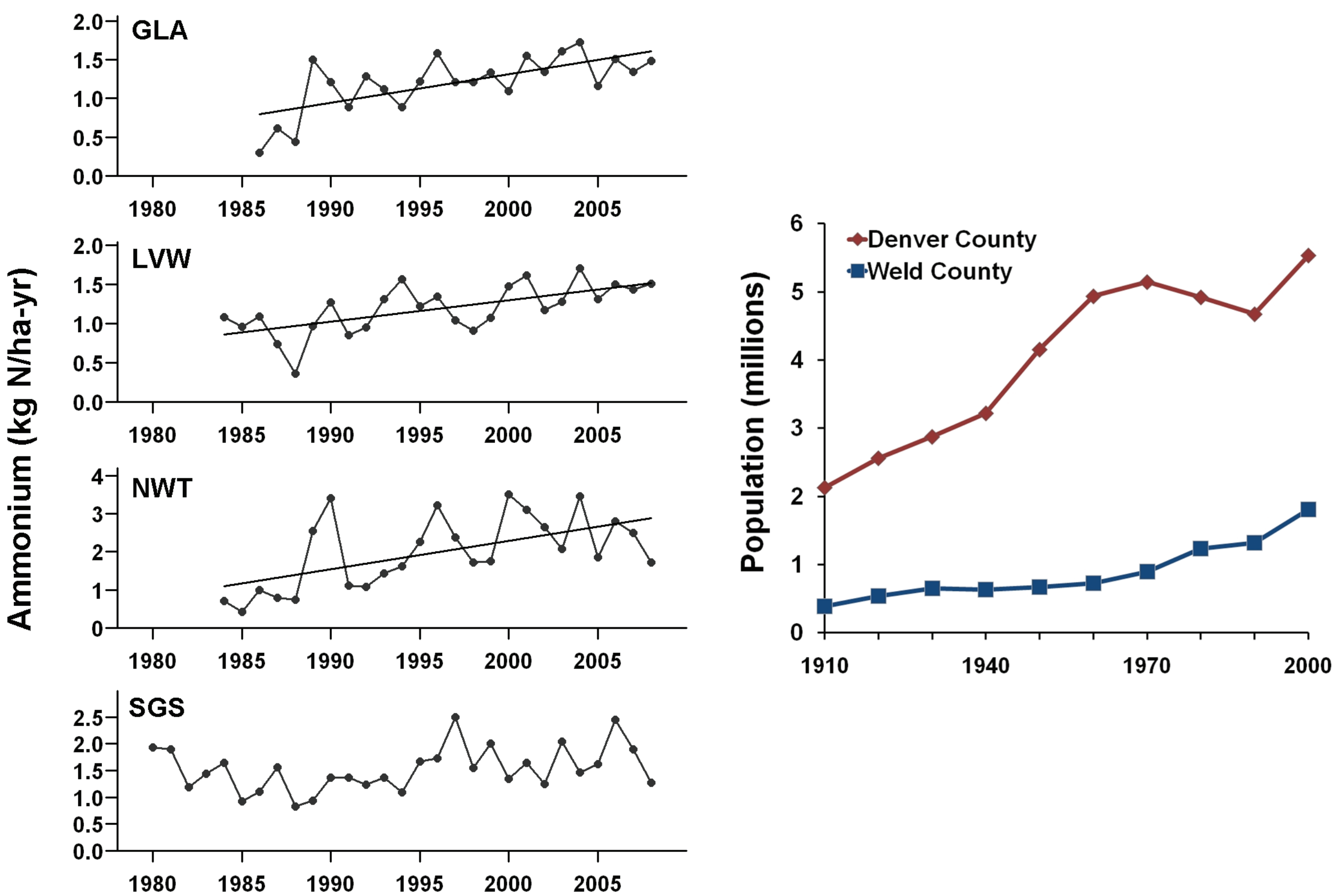

Figure 6-4. Left panel: An increase in ammonium deposition (kg/ha-yr) at three upslope Rocky Mountain locations (GLA, LVW, NWT) and no trend at a grassland site (SGS). Right panel: Patterns in nitrogen deposition for mountain sites reflect high rates of population increase in metropolitan Denver (represented by Denver County), the main source of nitrogen in rainfall in spring and summer. The county of the grassland site (Weld) also increased in population, but the source of nitrogen deposition is rainfall from surrounding agricultural land and rangeland. (Original data from Internet home pages—see table 1-1, http://nadp.sws.uiuc.edu/, and http://www.census.gov. Synthesized data from http://www.ecotrends.info.)

Hypothesis 2. Changes in Atmospheric Deposition Are Related to Changes in Population Density for Some Sites

Sites in the Rocky Mountains show a different trend in nitrogen deposition than other sites in the West, and these patterns are related to location rather than to ecosystem type (figure 6-4 left panel). For three high-elevation sites in the central Rockies, ammonium (and nitrate, not shown) deposition has increased through time (GLA, LVW, NWT). These sites are located upslope to the west of the Denver metropolitan area along the Front Range of the Rocky Mountains where human population density has been rapidly increasing (figure 6-4, right). Spring and summer moisture at these mountain sites is influenced mainly by westerly upslope storms from the Front Range; these storms provide an important source of atmospheric nitrogen deposition (Burns 2003). Thus, a rapid increase in density of humans may explain, at least in part, the higher nitrogen deposition rates in the mountains. In contrast, the lack of a trend in ammonium (or nitrate) for grasslands at lower elevations east of the mountains (SGS) likely reflects the long distance and easterly location of this site away from the influence of the major cities along the Front Range.

Conclusions

Human activities have greatly altered patterns in atmospheric deposition over the past 20 years. Effects of these activities vary regionally and across the continent as a result of variation in factors such as human population density, energy and agricultural production and use, atmospheric circulation and sources of rainfall, and government regulation. Cross-site comparisons of long-term data provide new insights into these spatial patterns.

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Chapter 7

Cross-Site Comparisons of Ecological Responses to Long-Term Nitrogen Fertilization

S.L. Collins, K.N. Suding, and C.M. Clark

Atmospheric pollution, as either wet or dry deposition, is changing through time for many ecosystems (chapters 6, 12). The long-term effects of these changes on ecosystem structure and function are not well understood, in particular for reactive nitrogen in the forms of nitrate (NO_3) and ammonium (NH_4). Reactive nitrogen is an essential nutrient that limits net primary production in most terrestrial and some aquatic ecosystems (Vitousek and Howarth 1991, Elser et al. 2007). Atmospheric nitrogen deposition is considered one of the major drivers of diversity loss in ecosystems (Sala et al. 2000), though land-use change remains the most important factor.

Given that human activity has doubled available nitrogen (Vitousek et al. 1997) along with other key resources (such as phosphorus) and that net primary production is increasing globally (Nemani et al. 2003) with variable patterns in time and space at specific sites (chapters 5, 14), a more mechanistic understanding of the relationship between nitrogen availability, productivity, and species diversity is needed.

The following key questions remain unanswered:

- How do increasing resources other than nitrogen affect productivity and species diversity?
- What are the mechanisms that can cause diversity to decline as productivity increases?
- Does an increase in productivity directly or indirectly through other environmental variables (such as pH) affect species diversity?
- How do microbial communities and processes respond as resource availability increases?
- Can plant functional trait responses provide a mechanistic understanding to the relationship between productivity and diversity?

Long-term observational and experimental data are needed to address these important research questions. For example, a long-term nitrogen fertilization study at the Cedar Creek LTER site in Minnesota (CDR) provides an interesting example of both threshold changes in species abundance and loss of diversity with addition of resources. In this experiment, about 10 g/m of nitrogen has been added annually to an abandoned agricultural field since 1982. Species diversity declined rapidly in response to nitrogen fertilization, whereas diversity in control plots fluctuated from year to year in response to interannual changes in precipitation. Consequently, the abundance of a non-native annual C_3 grass, *Agropyron repens,* increased relatively rapidly while the abundance of a long-lived clonal C_4 bunchgrass, *Schizachyrium scoarpium,* decreased relative to controls (figure 7-1). Thus, chronic environmental change can cause rapid, nonlinear transitions in local distribution and abundance of plant species.

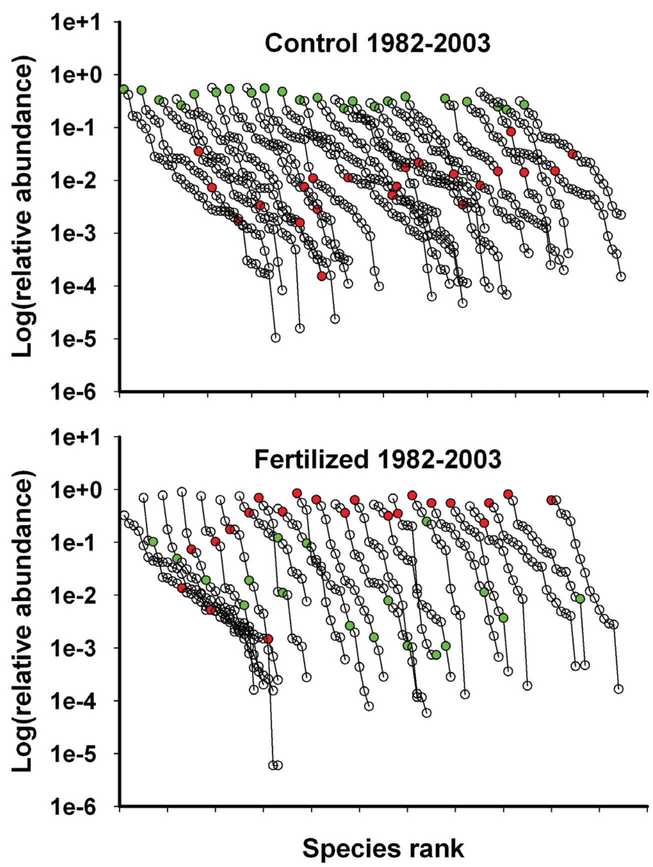

Figure 7-1. Annual rank-abundance curves for (a) control and (b) fertilized plots at the Cedar Creek Ecosystem Science site (CDR) for Field C from 1982 to 2003 show the relative ranking of a late successional, perennial C_4 grass *(Schizachyrium scoparium)* (green filled circles), and an early successional, annual C_3 grass *(Agropyron repens)* (red filled circles) (Collins et al. 2008). The curves show how the ranks of *Schizachyrium* and *Agropyron* remain relatively constant in control plots, but they rapidly reverse order in fertilized plots. Reprinted with permission from the Ecological Society of America.

Extrapolating cause and effect relationships from one ecosystem to another is often challenging, whereas multisite analyses of similar fertilization experiments across systems can provide greater generality. In a multisite analysis of plant community responses to experimental addition of nitrogen (100 kg/ha in most cases), plant species richness declined by about 30 percent and aboveground net primary production (ANPP) increased by about 50 percent across a range of sites with different initial productivity potentials (figure 7-2). This loss of diversity also occurs along natural productivity gradients (Stevens et al. 2004). Despite these common responses across sites and systems, the mechanisms causing this decline in diversity as productivity increases are still being debated, and long-term responses have not been evaluated.

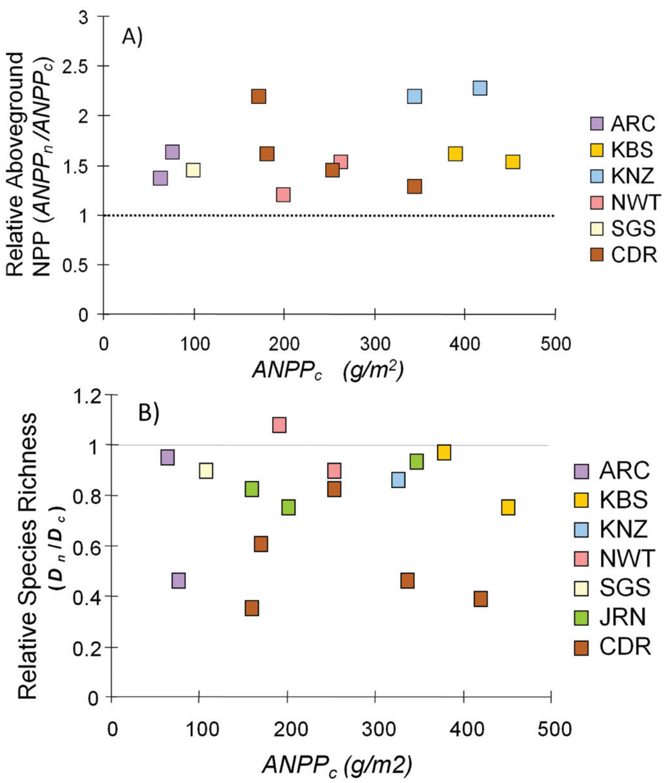

Figure 7-2. Response ratios for the last year of data for seven grassland sites receiving long-term N additions of 9 to 13 g/m^2/yr. (A) $ANPP_n$ in fertilized plots over $ANPP_c$ in control plots versus mean $ANPP_c$ of control plots. (B) species richness in fertilized plots (D_n) over species richness in control plots (D_c) versus mean $ANPP_c$ of control plots. Dashed lines indicate a response ratio of 1, meaning the N fertilization plots show no difference from control plots. (Redrawn from Gough et al. 2000.)

Functional traits may provide mechanistic insights into a plant community's response to fertilization (Bai et al. 2004). Species traits reflect evolutionarily derived strategies for resource capture and interspecific interactions, which influence community structure and ecosystem processes (Diaz and Cabido 2001). An analysis of more than 900 species responses from 34 nitrogen fertilization experiments across North America showed that both trait-neutral mechanisms (for example, rarity) and trait-based mechanisms (such as plant height) operated simultaneously to influence diversity loss as production increased (Suding et al. 2005). Thus, rarity, species identity, and functional traits affect species responses to increasing productivity in long-term nitrogen fertilization experiments. Because these responses may be highly dependent on context, they challenge our ability to predict how communities will change as the amount of reactive nitrogen continues to increase globally.

Conclusions

Human activities have greatly altered the nitrogen cycle. As a consequence, net primary production has increased globally and biodiversity has decreased in many herbaceous plant communities. Trait-based analyses may provide insight into the mechanisms behind biodiversity loss in response to increased nitrogen availability. Long-term studies are needed to document these patterns under variable climatic conditions.

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Chapter 8

Long-Term Trends in Human Population Growth and Economy Across Sites

C.G. Boone, T.L. Gragson, and J M. Grove

Human activities play profound roles in ecosystem dynamics, both directly through land use change, spread of invasive species, and increases in air and water pollution and indirectly through increases in atmospheric carbon dioxide (CO_2) and trace gases that modify climate and weather patterns. Rapid growth in the global human population during the last century, from 1.6 billion in 1900 to 6.7 billion in 2008, has increased demands for resources with subsequent effects on biotic (plants, animals, microbes) and abiotic (soils, atmosphere, water) properties of ecosystems. These changes in ecosystem properties result in modifications to the goods and services provided to humans. Thus, a feedback loop exists between human populations and their environments that makes it imperative that trends in human populations be examined as both a key driver to changes in ecosystems, and as a key responder to changes in those same systems.

Although human population is rising globally, the distribution is not uniform and varies spatially, even across the United States (figure 8-1). The Eastern United States is more heavily populated than the West, although parts of the West have experienced some of the highest rates of increase over the past 50 years (chapter 13). In particular, between 1990 and 1998, the Phoenix metropolitan area grew faster—a 31-percent rate of increase—than any other metropolitan area in the United States. (National average rate was 8.7 percent.)

Figure 8-1. Night lights show spatial variation in human population density across the United States. (Http://veimages.gsfc.nasa.gov//1438/land_lights_16384.tif.)

These increases in human populations throughout the country influence the ecological dynamics of research sites adjacent to urban areas as well as noncontiguous sites. Many research sites in this book were originally located in relatively pristine areas with low direct human impacts. As human populations have increased through time, housing and urban developments are moving closer to these formerly pristine areas. Although most research sites allow restricted or limited access to the public, the spread of native and exotic plants and animals from residential areas to nearby research areas is difficult to control. In addition, human activities upslope or upwind of research areas can influence those ecosystems through the transport of seeds, particulates, chemical compounds, water, soil, and nutrients by water, wind, and animals. This transport of materials can occur locally from a nearby city (figure 6-4) or over large distances, such as sediment loads from the upper Mississippi River deposited in the Gulf of Mexico.

Thus, we need to understand how human populations are changing in demographic and socioeconomic variables that directly influence nearby research sites. We also need to know the broader context of change in these variables across the country and how these changes influence patterns in migration and economic policies that can influence noncontiguous areas. Comparing human population and economic variables through time and across space (chapter 13) for the same set of sites where detailed ecosystem properties are measured (chapters 11, 12, 14) provides an opportunity to directly link these important elements of coupled human-natural systems.

In this chapter, we illustrate the value of long-term data in testing two important hypotheses related to spatial variation in trends in coupled human-natural systems and present a case study of cross-site comparisons made possible with population and economic data from different locations across the country. Long-term graphs of human population and economy data by site are in chapter 13.

Hypothesis 1. Tree Canopy Cover and Socioeconomic Status Are Positively Correlated in Both Urban and Suburban Counties

Tree canopy cover in both urban and suburban areas is largely a function of human population density, socioeconomic status, and lifestyle preferences. Although ecosystem properties such as water or soil nutrients can be limiting factors, these limits can be overcome through human intervention, including infrastructure, such as amendments to soil and irrigation, and management regimes including fertilizer application. These interventions along with maintenance of trees and available land for planting require resources. We hypothesize that variability of canopy cover in urban and suburban neighborhoods is explained primarily by the demographic and socioeconomic characteristics of those neighborhoods (Troy et al. 2007). A complementary hypothesis is that present-day canopy cover is a function of past socioeconomic characteristics of neighborhoods and that a “lag effect” can be detected through appropriate analysis of historic census data. Both long-term ecological data on canopy cover and human economic data collected by a suite of sites can be used to test this hypothesis (Boone et al. 2009).

Hypothesis 2. Health-Related Ecosystem Services Follow an Inverted U Relationship

Environmental conditions that affect human health, such as air pollution, are significantly affected by changes in the economy. We hypothesize that as the economy transitions from agriculture to manufacturing, either in locations or over time, air pollution will worsen. By contrast, as the economy shifts from manufacturing to a service economy, air quality will improve. The same inverted U relationship (known as the Environmental Kuznets Curve) is expected to develop with increases in income per capita. This hypothesis could be tested using air quality data obtained as the number of EPA nonattainment days per year for criterion air pollutants or as atmospheric deposition data in chapter 12 combined with economic data in chapter 13.

Case Study: Patterns in Human Population Growth Across the Country

Prior to this project and book, patterns in human population and economy variables had not been systematically examined for ecological research sites. Historically, most sites focused on collecting ecological data. In 1994, two LTER sites, NTL and CWT, were funded to incorporate a regional human dimension. In 1997, two LTER sites, BES and CAP, were funded as coupled human-natural systems with objectives directly related to studying human systems as part of the ecological system. More recently, the LTER Network published a document that describes a critical need for coupled human-natural systems research at all LTER sites (LTER 2007). This new direction for the LTER Network reflects an increasing recognition that humans are an integral part of all ecological systems. Thus, effects of both direct drivers (such as land use) and indirect drivers (such as climate change) of human systems on their environment must be studied in addition to studying feedbacks from ecological systems to human systems.

As a first step in studying these coupled systems, we examine spatial variation in trends in human populations with a focus on the percentage of the population that is urban. Although the United States in general is becoming more urban (Brown et al. 2005), we expect that the rate of change in urbanization varies across the country. We also acknowledge that some parts of the country are less urbanized than others. We selected six sites in different parts of the country to illustrate spatial variation in demographic change. Three of these counties were mostly urban in 2000: Santa Barbara, CA; Maricopa, AZ; and Miami-Dade, FL. The population data obtained from the U.S. Census Bureau show that these counties had very different patterns in the rate of change in urbanization through time (figure 8-2). Miami-Dade county in the southeastern United States, where the FCE LTER site is located, was more than 60 percent urban by 1920, whereas counties in the West became urbanized later: Santa Barbara County (SBC LTER) by 1930 and Maricopa County (CAP LTER) by 1950.

Three other counties were selected that were less than 80 percent urban in 2000—Dona Ana, NM; Grafton, NH; and Weld, CO (figure 8-3). These counties had similar rates of change until 1970 even though they are in different parts of the country. The increase in the populations of Doña Ana County (JRN LTER) and Weld County (SGS LTER) starting in 1970 reflects the migration of people from the north and west to the moderate climate of the Southwest and the Front Range of the Rocky Mountains. The county in New Hampshire surrounding the HBR LTER site remains mostly rural. These differential patterns in urbanization provide a template and stratification for future studies that link human populations with their environment.

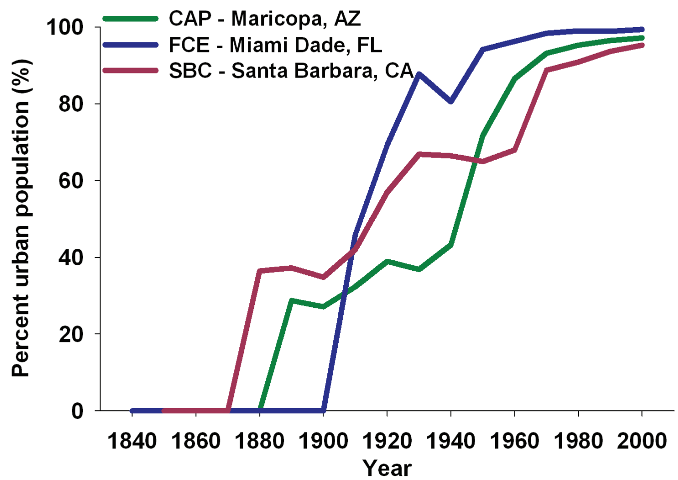

Figure 8-2. Percentage of the population in each county that was urban in each year of the U.S. census for three counties associated with LTER sites that are currently nearly 100 percent urban: Central Arizona-Phoenix (CAP), Florida Coastal Everglades (FCE), and Santa Barbara Coastal (SBC). (Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.)

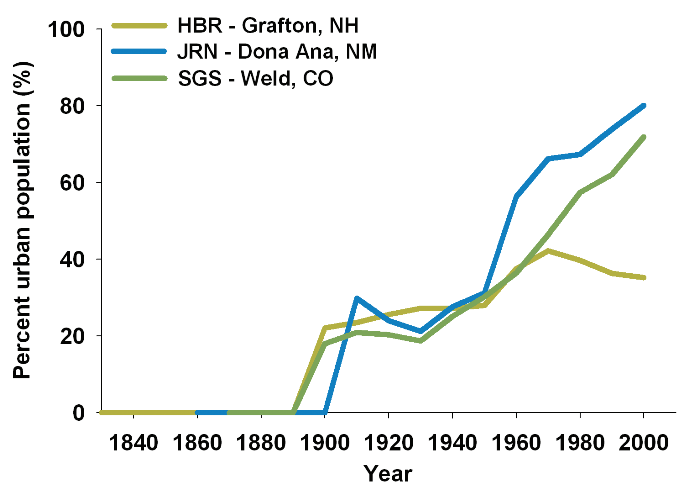

Figure 8-3. Percentage of the population in each county that was urban in each year of the U.S. census for three counties associated with LTER sites that are currently less than 80 percent urban: Hubbard Brook Ecosystem Study (HBR), Jornada (JRN), and Shortgrass Steppe (SGS). (Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.)

Summary

Since 1920, the majority of the human population of the United States has lived in urban areas. In the past few decades, urbanization rates have been particularly rapid in the West. Timing of growth affects the nature of urban expansion across the country because of the variation in policies, availability of technologies, and cultural norms that dominate over time. Especially since World War II, urban growth has been characterized by low-density development on the periphery of cities. This urban expansion can have direct effects on surrounding ecosystems through land use change and indirect affects through resource consumption, nutrient transport, and waste generation. In turn, alterations to ecosystem structure and function can affect availability of ecosystem services and human outcomes and behavior. Therefore, integrating human and ecological systems is critical to understanding the feedbacks and linkages that affect both and to develop better management systems.

Long-term demographic data are valuable for testing variations in social-ecological systems across space and time. We hypothesize that variation in vegetation cover in urban areas reflects demographic characteristics more than biophysical limits and that past demographics may be better predictors of vegetation, especially tree canopy cover, than present population characteristics. Long-term census data coupled with ecological data could be used to test the Environmental Kuznets Curve hypothesis, that as the economic base shifts from agriculture to manufacturing to services, air quality will worsen then improve. Variability across LTER sites through time provides a rich dataset for testing socioecological dynamics.

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Chapter 9

Disturbance Regimes and Ecological Responses Across Sites

D.P.C Peters, A.E. Lugo, F.S. Chapin III, A.J. Tepley, and F.J. Swanson

A disturbance is defined as a discrete event with the capacity to alter the structure, functioning, and species composition of an ecosystem (White and Pickett 1985). A number of different disturbances that affect ecosystems fall into four major classes: climatic, physical, biotic, and anthropogenic (figure 9-1). The effects of a particular disturbance event depend on its duration (short or acute vs. chronic or long-term) and intensity, how large an area it affects, the state of the ecosystem at the time of disturbance (whether the system is mature or young, in active growth, or dormant), and the frequency of return of the disturbance. Some disturbances occur frequently but at low intensity, such as annual fires that move quickly through forest understories. Some are very infrequent but of high intensity, such as volcanic eruptions or category 5 hurricanes. And others exhibit a wide range of frequency and intensity combinations, such as the size and frequency of landslides on forested landscapes.

Figure 9-1. Examples of four classes of disturbance based on the type of driver. Top left: Physical—wildfire in Alaska, Bonanza Creek Experimental Forest (BNZ), photo by F. Chapin. Top right: Climatic—hurricane in Puerto Rico, Luquillo Experimental Forest (LUQ), photo by N. Brokaw. Bottom left: Biotic—salt cedar invasion along the Rio Grande, Sevilleta (SEV), photo by J. Thibault. Bottom right: Anthropogenic—housing development abutting desert in the Phoenix metropolitan area, Arizona, Central Arizona-Phoenix (CAP), photo by CAP photo gallery.

Disturbances affect ecosystems in almost limitless ways and extend beyond the initial effects that are usually visible to the human eye. A cascade of effects involving the functioning, restructuring, and other changes (succession) in an ecological system follows the immediate visible effects of the disturbance. As an example, figure 9-2 shows a 60-year record of structural changes in a subtropical wet forest in Puerto Rico (LUQ) following the passage of a hurricane 10 years before data collection began followed by two more recent hurricanes (Drew et al. 2009). Both the trend (increase, then decrease) and magnitude of change depend on the response variable. These dramatic long-term changes in tree density, biomass, and species diversity and evenness were accompanied by equally significant changes in nutrient cycling, species composition, primary productivity, and rates of mortality and regeneration (Lugo 2008, Drew et al. 2009).

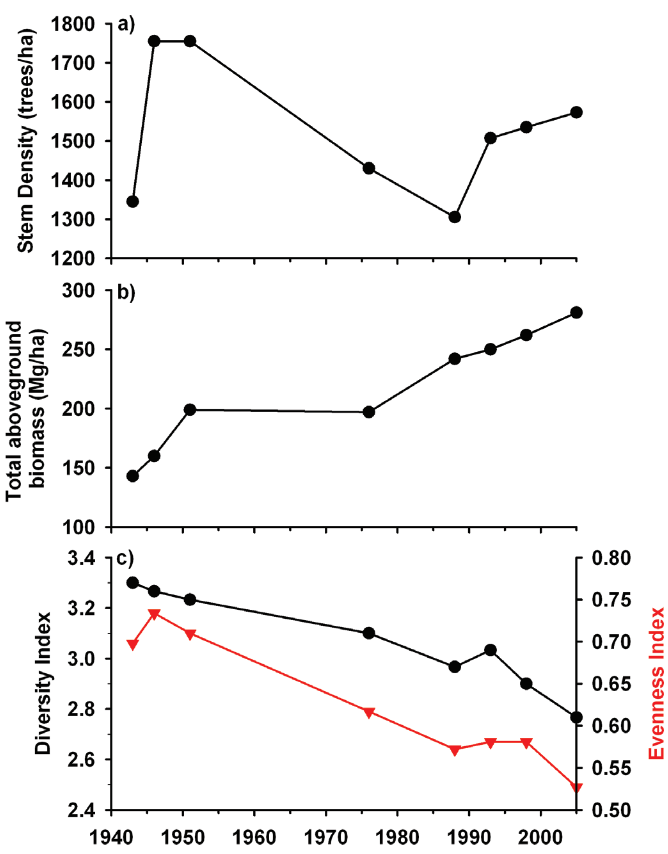


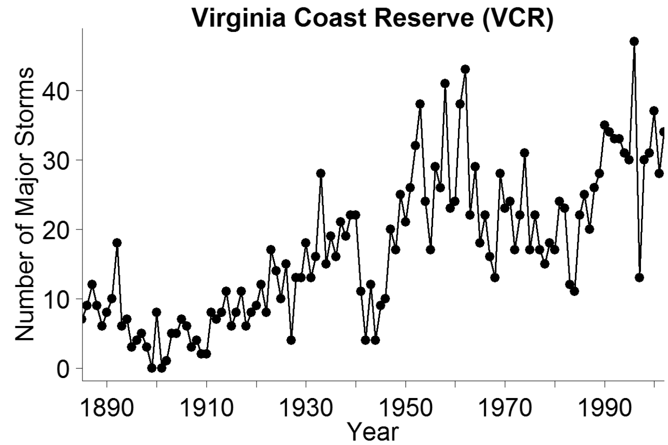
Figure 9-2. (a) Tree stem density; (b) total aboveground biomass (leaves and wood); and (c) Shannon-Weiner plant species diversity (black line) and overall evenness index (Pielou's J) (red line) of trees through time in Puerto Rico, following a hurricane in 1930, Luquillo Experimental Forest (LUQ). Two additional hurricanes influenced forest dynamics: Hugo in 1989 and Georges in 1998 (Drew et al. 2009). Modified with permission from Interciencia.

For many disturbances, long-term data are needed to unravel their effects. A long return interval between disturbance events requires a long period of study to capture multiple events. However, the field of ecology is a recent historical development that spans about 100 years, and the simultaneous monitoring of ecosystem structure and functioning has less than 50 years of experience. Moreover, the focus of this activity has been on a few ecosystem types. Thus, the scientific opportunity to understand how events with recurrence intervals of greater than 100 years affect ecosystem processes has been very limited.

Two circumstances complicate the study and understanding of the effects of disturbances on ecosystems. First**,** interactions between different disturbance events can create greater effects than each disturbance alone, or these interactions can mask the effects of individual events. As an example, fires often follow hurricanes, and fires can be followed by debris flows. When one disturbance event follows another, determining what effects to attribute to each event is difficult. In some cases, it can even be difficult to identify the disturbance that resulted in the dramatic effects on an ecological system. For example, in 2001-2002, the salt marshes of coastal Georgia (GCE) experienced a sudden dieback that affected large patches (up to 240 ha) of both salt marsh cord grass *(Spartina alterniflora)* and black needlerush *(Juncus roemerianus)* (Ogburn and Alber 2006). A number of hypotheses have been advanced to explain the dieback, which was associated with an extreme drought (Silliman et al. 2005, Alber et al. 2008). To date, no single factor has been unambiguously linked to all dieback events, and it is possible that multiple factors interacted to produce dieback at different sites. Plant densities have increased at affected sites, but at varying rates—some sites appear to have fully recovered while others still have sparse vegetation (figure 9-3).

Second, the number, spatial extent, and frequency of occurrence of disturbance events are changing as a result of human activity. These activities can have both direct and indirect effects on ecosystems (chapter 8). For example, frequency and intensity of fires are increasing in some areas, likely as a result of human activity that includes increasing temperatures (figure 9-4) (Kasischke and Turetsky 2006). The increase in frequency of major storms along the Atlantic coast (Hayden and Hayden 2003), with consequences for shoreline location, may also be related to climate change (figure 9-5) (Harris 1992, Shao et al. 1998). Trends in climate for each site are shown in chapter 11.

Ecologists have the dual challenge of understanding the effects of natural and anthropogenic disturbances on ecosystems and at the same time understanding how changing ecological systems can modify the characteristics of subsequent disturbances. Of particular interest are the effects of disturbances on the services that society requires to sustain human populations and economies and the conservation of species assemblages and ecosystems.



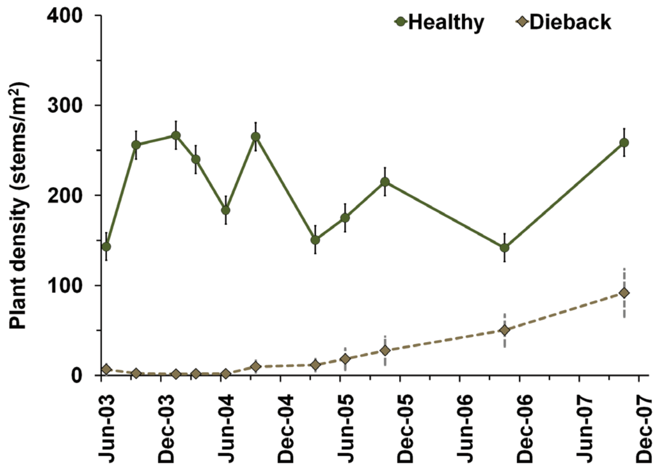


Figure 9-3. Regrowth of *Spartina alterniflora* at a marsh dieback site in coastal Georgia (GCE). Samples collected at dieback (dashed line) and nearby healthy (solid line) areas (Alber et al. 2008). Reprinted with permission from Elsevier.

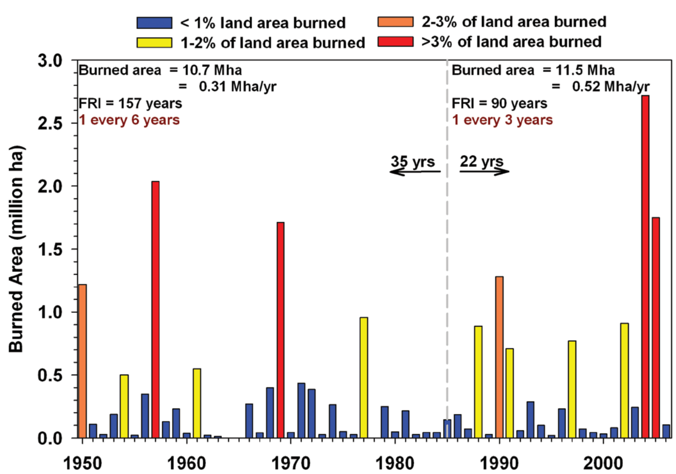


Figure 9-4. Area burned in North America's northern forest, which spans Alaska and Canada, tripled from the 1960s (Fire Return Interval [FRI] 1 every 6 years) to the 1990s (FRI 1 every 3 years). Two of the three most extensive wildfire seasons in Alaska's 56-year record, based on area burned, occurred in 2004 and 2005; and half of the largest fire years have occurred since 1990. Modified from Kasischke and Turetsky 2006.

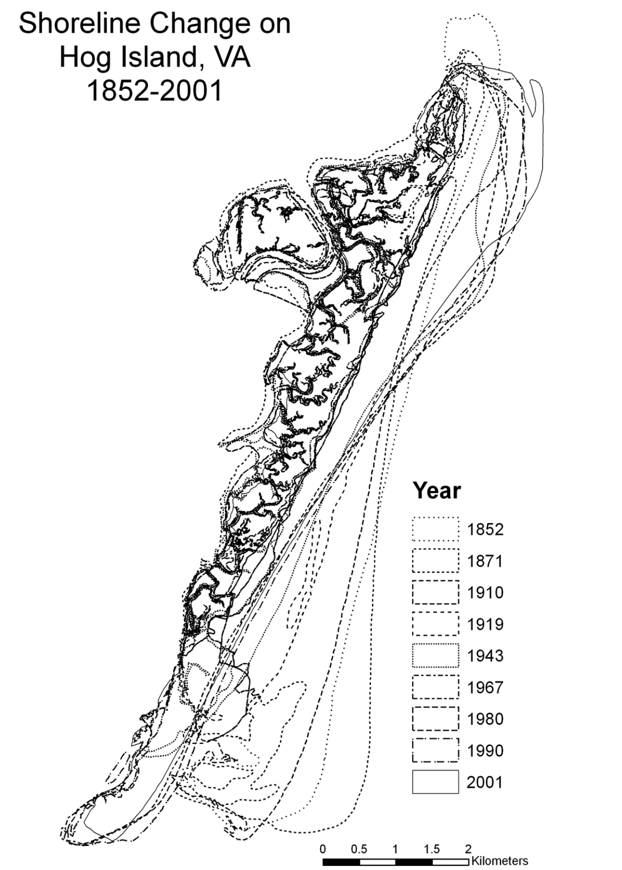


Figure 9-5. Number of major storms along the coast of Virginia, Virginia Coast Reserve (VCR), has increased since 1950 (top: modified from Hayden and Hayden 2003; data from http://amazon.evsc.virginia.edu) with associated changes in the shoreline of Hog Island, VA (bottom: modified from Harris 1992, Shao et al. 1998). Over 90 percent of the current upland area on Hog Island is newly deposited since the late 1800s. Data compiled based on historical maps (1852-1919), aerial photos (1943-1990), and satellite imagery (2001).

In this chapter, we first present characteristics of disturbances and then discuss ecosystem responses for each of four major classes of disturbance. Because specific disturbance events vary among sites and ecosystem types, we use examples from a variety of sites to illustrate the importance of long-term data in unraveling the role of disturbances in ecosystem dynamics. Quantitative cross-site comparisons are currently not possible for many types of disturbance as a result of nonstandardized methods of data collection, archiving, and retrieval (chapters 16, 17), although recently a framework was developed to "unpack" the drivers and responses associated with disturbance events to allow cross-site comparisons (Peters et al. 2011).

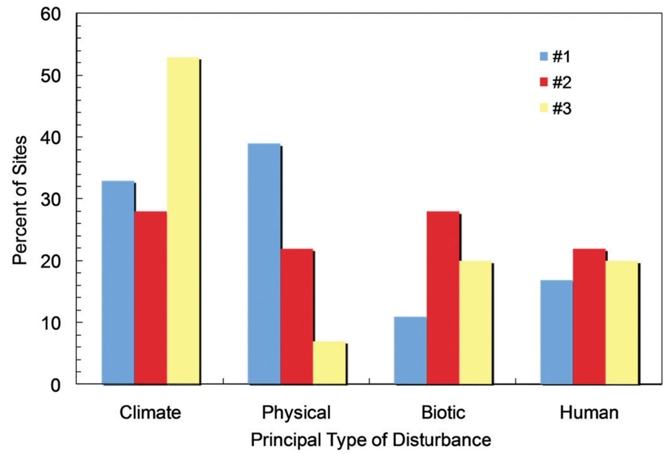


Figure 9-6. In a survey of lead scientists from the 26 LTER sites, physical and climatic disturbances were identified as the most important classes at their site (ranked #1). All four disturbance classes were equally important as the second most important type (ranked #2) (Peters et al. 2011).

Disturbance Characteristics

Each of four major classes of disturbance (climatic, physical, biotic, and anthropogenic) can have different effects on ecosystems. For example, windstorms are climatic disturbances that mechanically alter the structure of forests and transfer biomass from the forest canopy to the soil surface where it can be processed by microorganisms. In contrast, wildfires are physical disturbances that consume organic matter and release ash plus carbon dioxide gas into the atmosphere. Another class of disturbance includes those that affect ecosystems biologically, such as insect attacks on trees or defoliation by herbivores. Anthropogenic (human-caused) disturbances include the clearing of trees or cultivation of agricultural land as well as atmospheric warming and ozone pollution.

In general, physical and climatic disturbances are the most important classes driving dynamics at many sites (figure 9-6) (Peters et al. 2011). However, the disturbance regime of a site can include all four classes, each with a characteristic spatial extent and frequency of occurrence (figure 9-7) (Peters et al. 2008). At some sites, climatic disturbances (like hurricanes or drought) are the most prevalent class, with multiple disturbance events occurring through time at a site (figure 9-8).

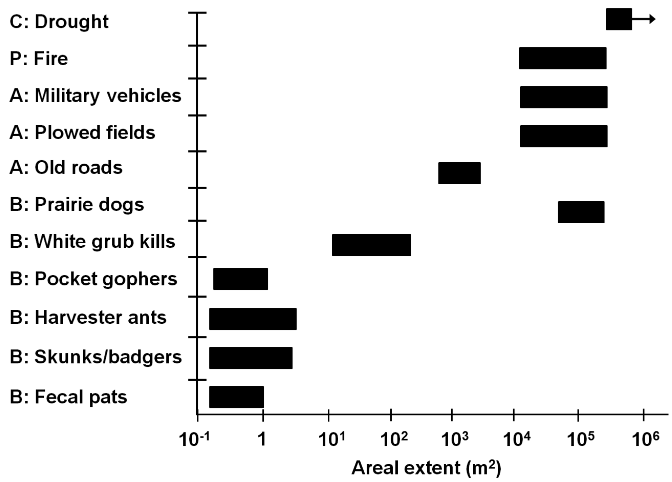


Figure 9-7. The disturbance regime in the Shortgrass Steppe (SGS) consists of all four types of disturbances that vary in spatial extent: C, climatic; P, physical; A, anthropogenic; and B, biotic. Modified from Peters et al. 2008.

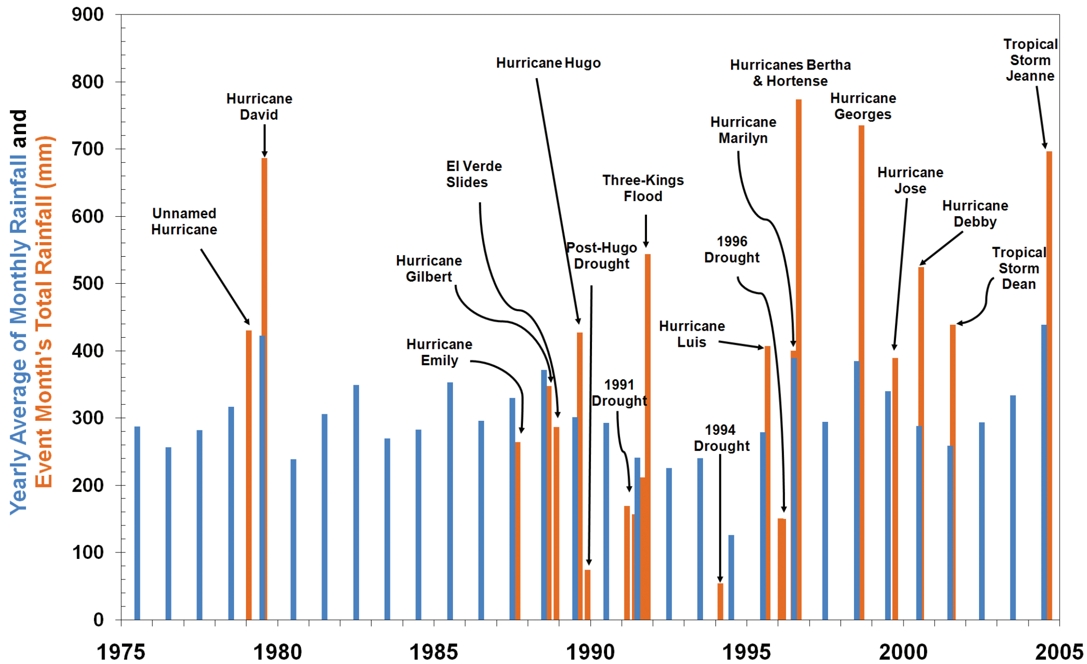


Figure 9-8. Multiple disturbance types often occur at one site as parts of the disturbance regime, for example, at Luquillo Experimental Forest (LUQ). However, physical disturbances (hurricanes) are the most prevalent at LUQ. Data from W. McDowell, D. Schaefer, A. Estrada-Pinto, A. Ramírez, and National Climatic Data Center. (http://www.ncdc.noaa.gov.)

Ecosystem Responses by Disturbance Class

Climatic Disturbances

Extremely high or low conditions of climatic drivers can have profound effects (chapters 3, 11). In many cases, the resulting disturbance is a combination of extreme events of multiple climatic drivers. Hurricanes are extreme climatic events with high wind speeds of more than 33 m/s, storm surges over 1.0 m, barometric pressure under 908 millibars, and variable rainfall sustained over several days in one location. Hurricanes move across landscapes to influence large areas. In the United States, the most frequent, intense hurricanes occur along the Atlantic Coast, moving northward from the Gulf of Mexico or Florida to the Northeastern States.

Long-term data show that hurricanes are more frequent and more intense in Puerto Rico (LUQ) than in New England (HFR) because storms decrease in intensity as they move across land (figure 9-9). Both locations have had periods with more events than others, although these events did not occur during the same period (1950-1960 at HFR; 1890-1900 at LUQ) (Boose 2003). This spatial variation in occurrence shows that hurricanes do not follow the same tracks across land and water every time.

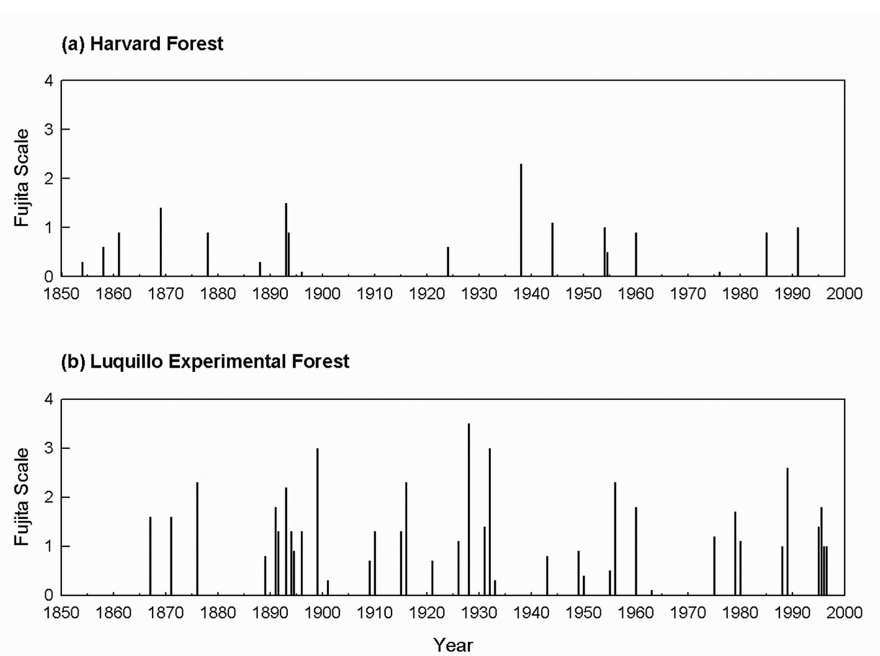


Figure 9-9. Years in which hurricanes occurred at two sites and their intensity based on the Fujito scale in which larger numbers are more intense events: (a) Harvard Forest (HFR) in the north-eastern United States and (b) Luquillo Experimental Forest (LUQ) in Puerto Rico (Boose 2003). Reprinted with permission from Oxford University Press.

The effects of hurricanes need to be examined within the context of other disturbances that affect an ecosystem. In Puerto Rico (LUQ), these other disturbances include high rainfall events due to passage of storms or frontal systems as well as droughts and landslides (figure 9-8). Populations of plants and animals respond in a variety of ways to these different events (figure 9-10). Snails maintain high population numbers during periods of frequent disturbance. Frogs increase after a hurricane with the creation of microsites for reproduction, but decrease rapidly during droughts. Shrimp in streams have an upward, although variable, trend, in spite of the disturbance regime, while birds showed lag responses to disturbance events.

Drought is another kind of climatic disturbance that affects many systems. A drought occurs when precipitation is sufficiently lower than average that ecological systems are affected. Low precipitation is often accompanied by high temperatures, low relative humidity, and low cloud cover such that a definition of drought needs to encompass multiple climatic variables. Indices such as the Palmer Drought Severity Index (PDSI) can be used to determine the beginning and end of a drought as well as its severity (chapter 11).

Drought occurs throughout the United States and globally, although its frequency and intensity vary regionally. In the Great Plains, the drought of the 1930s and the resulting Dust Bowl are often cited as the most extreme drought impacts over the past several centuries. In contrast, the 1950s drought was of longer duration and more extreme intensity in the Southwest, with major impacts on system dynamics. In southern New Mexico (JRN), the historically dominant perennial grass black grama *(Bouteloua eriopoda)* died out on most (64 percent) research quadrats (1 m^2)

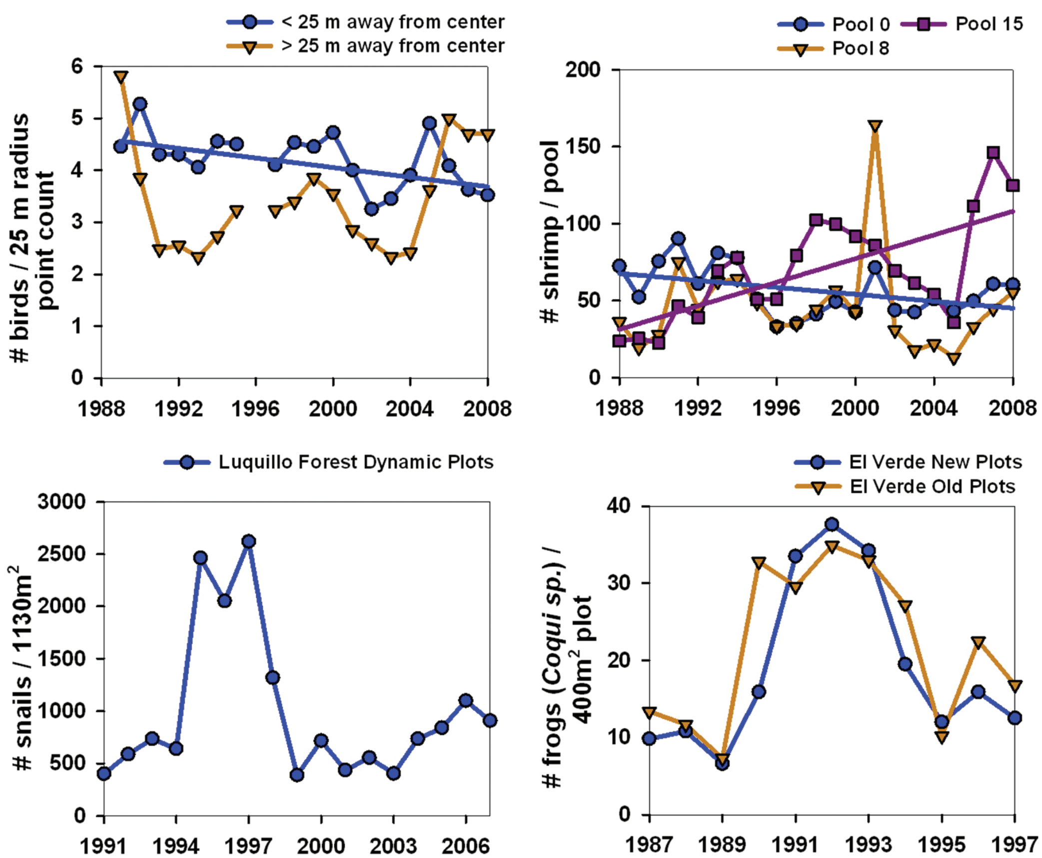


Figure 9-10. Response of different groups of organisms following multiple disturbance types in a forest in Puerto Rico. Data from R. Waide for birds, T. Crowl for shrimp, C. Bloch for snails, and L. Woolbright for frogs.

either during or shortly after the 1950s drought (figure 9-11). However, this species went locally extinct on 21 percent of research quadrats prior to that drought, probably because of a drought in the early 1900s in combination with livestock overgrazing (Peters et al. 2006). Persistence of this species to at least 1979 on 15 percent of the quadrats reflects spatial variation in vegetation dynamics that cannot be explained by broad-scale drivers such as drought and grazing.

Global warming, the increase in air and water temperatures, is a climatic disturbance that results from increases in carbon dioxide and other greenhouse gases in the atmosphere resulting from human activities (IPCC 2007). Increasing temperatures are an example of a chronic disturbance over a long period as compared to acute disturbances (events discrete in time). Ecological systems can respond to global warming in a number of ways. One effect of global warming is a shift in species distributions or abundances with changes in conditions for recruitment, mortality, and prey availability (figure 4-2). For example, glaciers are being lost in the Rocky Mountains as temperatures increase (figure A1-58).

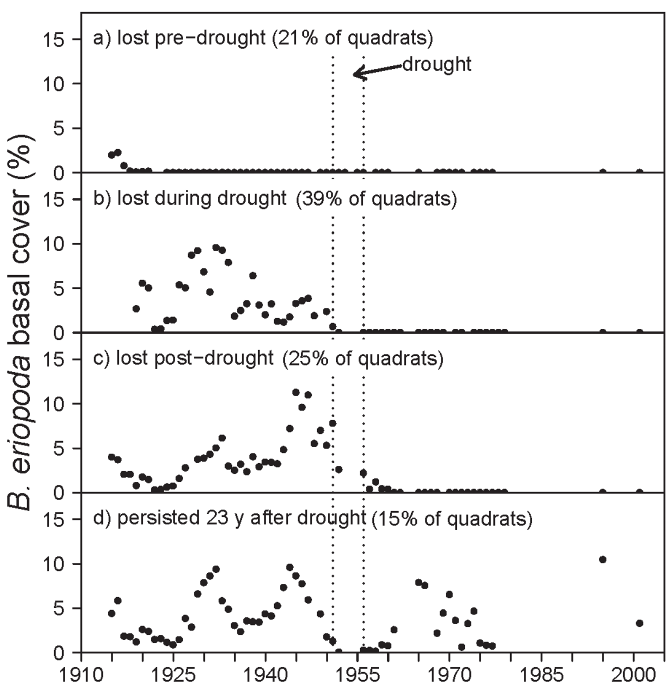


Figure 9-11. Black grama (*Bouteloua eriopoda*), the dominant perennial grass of upland grasslands in the Chihuahuan Desert, went locally extinct on most (64 percent) research quadrats (1/m^2) either during (b) or shortly after (c) the 1950s drought. However, this species went locally extinct on 21 percent of research quadrats prior to the drought (a) and persists to at least 1979 on 15 percent of the quadrats (d) (Peters et al. 2006). Reprinted with permission from the American Institute of Biological Sciences.

Physical Disturbances

Changes in abiotic conditions, such as soils, nutrients, and water have consequences for biotic responses. Wildfires, wave height in oceans, and landslide debris flows are good examples.

Wildfires remove aboveground plant biomass and result in the release of particulates to the atmosphere and addition of carbon and nitrogen to the soil. Fires occur across a range of intensities and spatial extents with variable effects on ecosystem dynamics. Fires are common features in grasslands and tundra with sufficient biomass to carry a fire and in forests where crown fires and understory fires are possible.

In the tallgrass prairie of Kansas (KNZ), fires induce pulses in the density of flowering stems of an important warm-season grass, big bluestem *(Andropogon gerardii)* (figure 9-12). Plant species composition

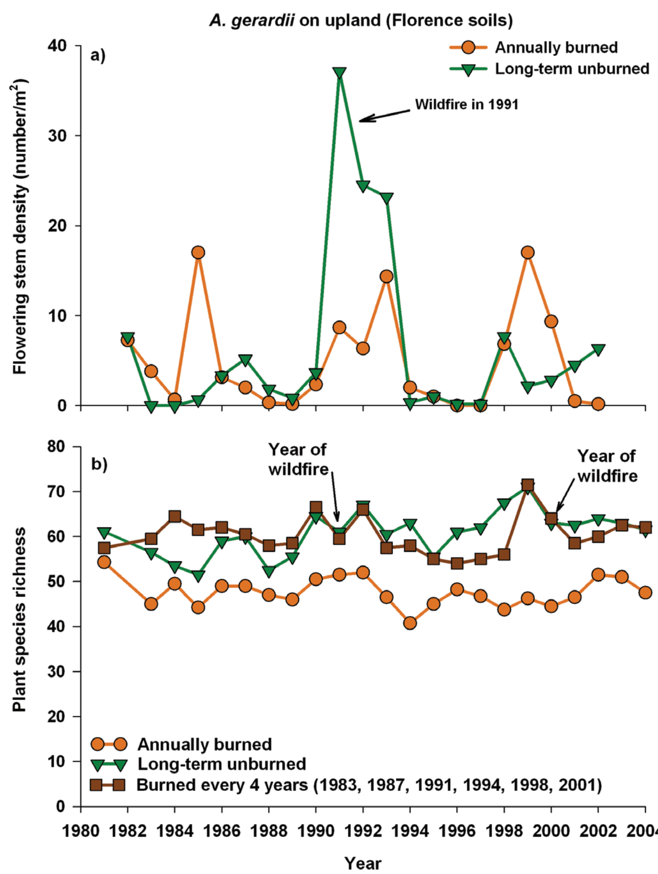


Figure 9-12. Wildfire in tallgrass prairie results in (a) a pulse in flowering stem density of *Andropogon gerardii*, an important perennial grass (data source: KNZ-PRE022; http://www.konza.ksu.edu; updated from Hartnett and Fay 1998), and (b) a decrease in plant species richness when it is burned annually compared with less frequent burns (updated from Knapp et al. 1998; http://www.konza.ksu.edu.)

is also affected by fire frequency. Annually burned watersheds have lower species richness than unburned or 4-year-burned watersheds (Hartnett and Fay 1998).

Much longer time periods for recovery can be required in some systems. In a semiarid grassland in central New Mexico (SEV), wildfire effectively limited invasion by the native shrub creosotebush *(Larrea tridentata)* (figure 9-13) (Parmenter 2008). Some plants were killed by fire, and the heights of remaining plants were reduced. It took 12 years for shrub height to recover to prefire levels.

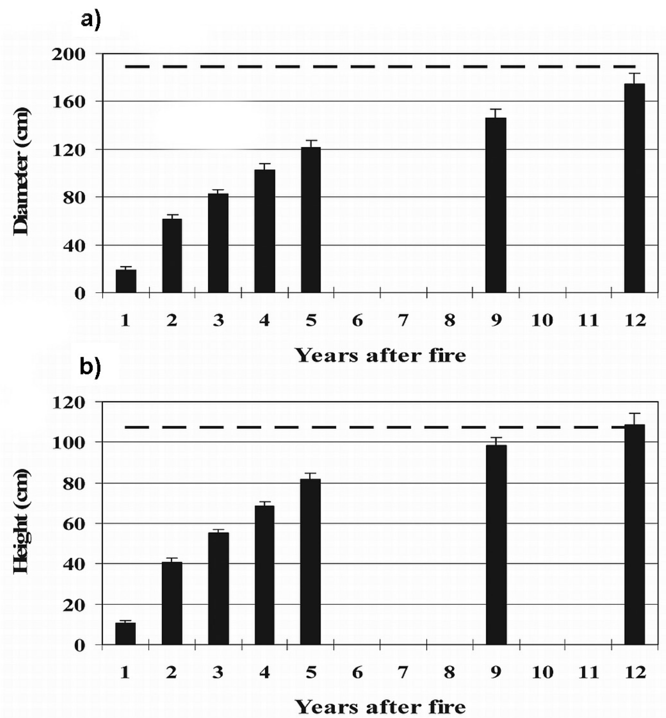


Figure 9-13. Diameter and height of *Larrea tridentata* (creosotebush), a common shrub in the Chihuahuan Desert, following fire at the Sevilleta (SEV) (Parmenter 2008). Twelve years' recovery was required before plants reached prefire height. Reprinted with permission from Allen Press Publishing Services.

Wildfire can also interact with other drivers in many systems. In coniferous forests of the Pacific Northwest (AND), centennial-scale variation in fire occurrence reflects climatic variability and human influences. Fire-history studies in western Washington and Oregon found two periods of extensive fires (the late 1400s to about 1650, and about 1800 to about 1925) (Weisberg and Swanson 2003). The increase in fire in the 19th century coincides with herding, logging, and mining by settlers, and the low abundance of fire throughout the 20th century corresponds to active fire suppression. Annual area burned in the 20th century also corresponds to climate, in particular the Pacific Decadal Oscillation (PDO) (Trouet et al. 2006). Warm phases of the PDO bring warmer-than-average winters with little snow, which may lead to long fire seasons with relatively low soil and fuel moisture.

Fire-history data (including establishment dates for 1,030 Douglas-fir trees in 124 stands) collected in the central western Cascades of Oregon (AND) suggests that the PDO also may have contributed to variation in the fire regime prior to the 20th century (Tepley 2010). Douglas-fir is a relatively shade-intolerant species whose regeneration depends on disturbances such as fire that open the canopy. In two large watersheds, major pulses of establishment by Douglas-fir were initiated during extended warm phases of the PDO (figure 9-14a, yellow bands) when tree-ring width was reduced, a likely indication of drought (Tepley 2010). As a result, 87 percent of Douglas-fir establishment dates fell in the intervals 1480-1610 and 1780-1940 (figure 9-14b), corresponding to previously identified periods of region-wide extensive fire. The correspondence of widespread establishment by this disturbance-dependent species with probable periods of drought during extended warm phases of the PDO suggests that the PDO may be an important factor in synchronizing widespread fire across the region.

Along coastlines, wave height shows high seasonal variability with storms that influence the standing crop of giant kelp (figure 9-15). Loss of giant kelp increases as wave height and storm intensity increase (Rassweiller et al. 2008).

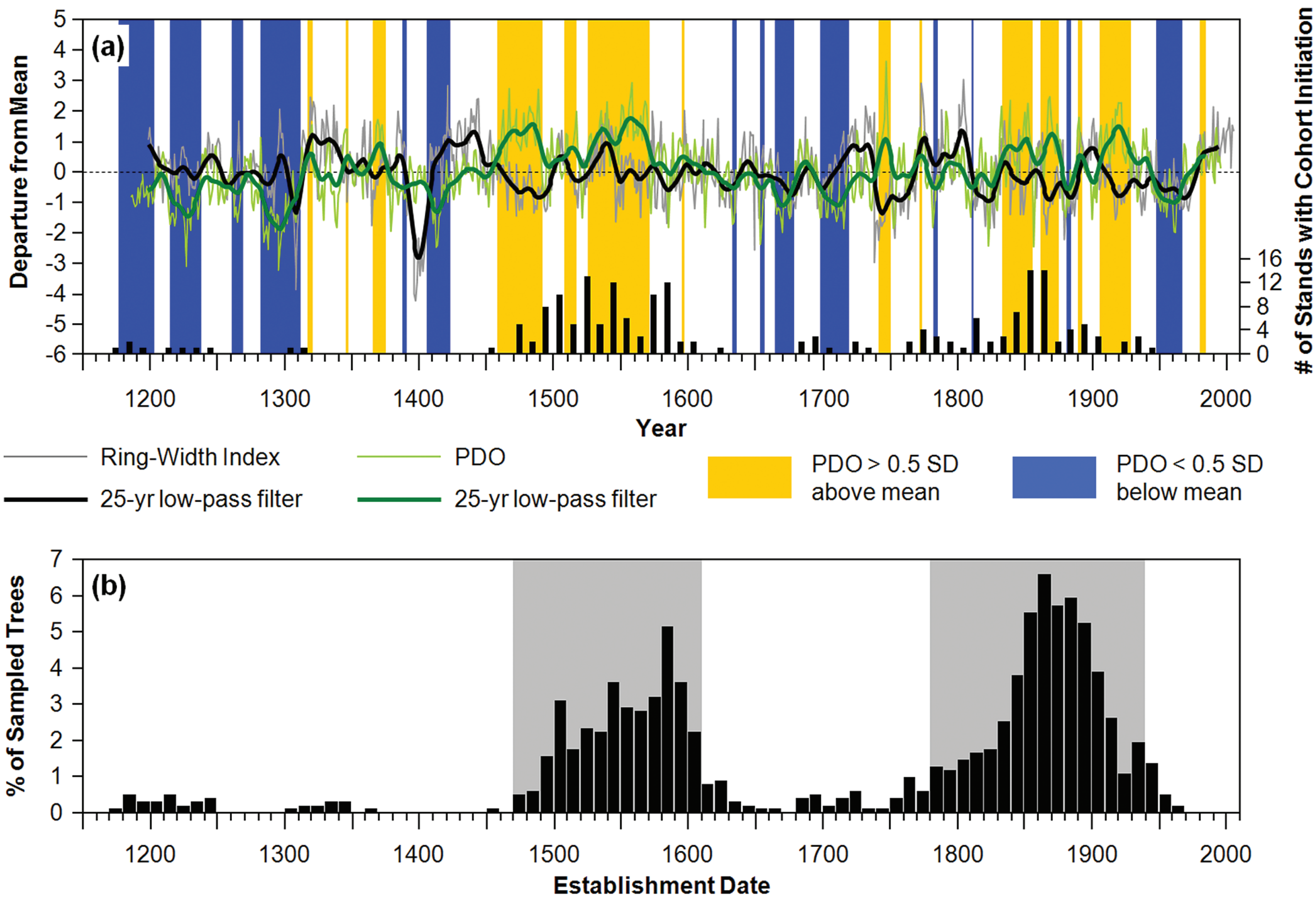


Figure 9-14. Comparison of (a) a tree-ring width chronology for some of the oldest Douglas-fir trees sampled in the central western Cascades of Oregon and a reconstruction of the Pacific Decadal Oscillation (PDO) (Tepley 2010). Yellow and blue shadings indicate extended warm and cold phases of the PDO, respectively. The histogram in the lower part of (a) shows the number of stands that recorded probable fire in that decade, based on an abrupt pulse of establishment. (b) Histogram of establishment dates for 1,030 Douglas-fir trees sampled at 124 stands in 2 watersheds, each totaling about 240/km. Gray shading indicates periods of abundant establishment that corresponds with regionwide periods of extensive fire (Tepley 2010).

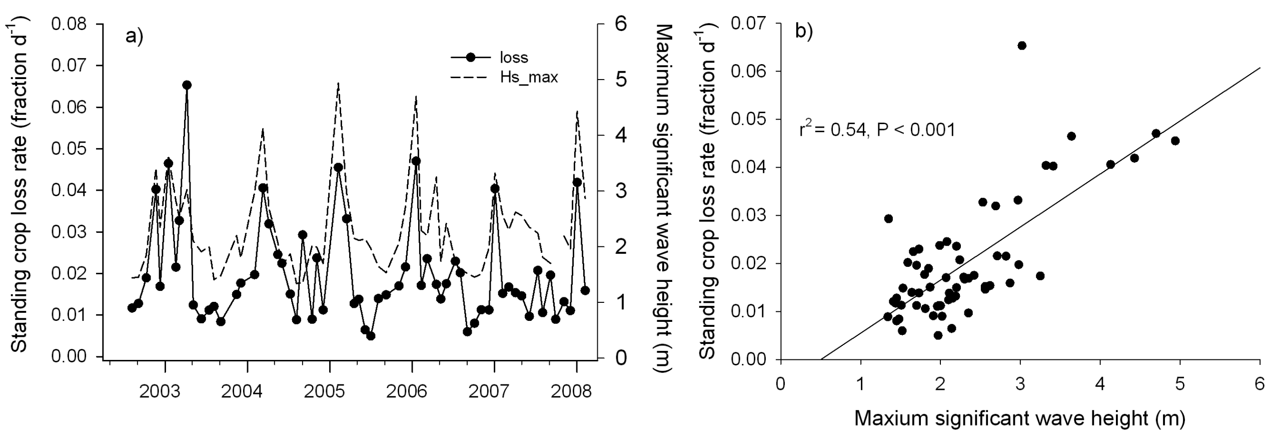


Figure 9-15. Wave disturbance and loss of kelp biomass off the coast of California, Santa Barbara Coastal (SBC). (a) The fraction of the standing crop of giant kelp lost per day each month at Mohawk Reef and the maximum significant wave height (Hs_{max}) during the monthly sampling interval. (b) The vast majority of kelp biomass lost episodically during winter when large waves remove entire plants, resulting in a strong positive relationship between the loss rate of kelp and maximum significant wave height. The lifespan of individual fronds is about 3 to 4 months, and the loss of fronds on surviving plants occurs continuously throughout the year. Wave data from NOAA Station 46053, E. Santa Barbara. Kelp data from Rassweiler et al. (2008).

Biotic Disturbances

Pest and pathogen outbreaks on plants and animals, and activities of animals that kill plants, as by burrowing, trampling, or herbivory are an important type of biotic disturbance. For example, feeding on the roots of perennial grasses by the larvae of june beetles (white grubs) resulted in patches of high mortality of the dominant grass (blue grama, *Bouteloua gracilis*) in 1977 at the SGS site in northern Colorado as compared with undisturbed areas (figure 9-16). Recovery of vegetation on grub-killed areas grazed by cattle and ungrazed areas were similar through time, in that perennial forbs dominated the patches in the first 3 years and were important components for the 14-year time period (Coffin et al. 1998).

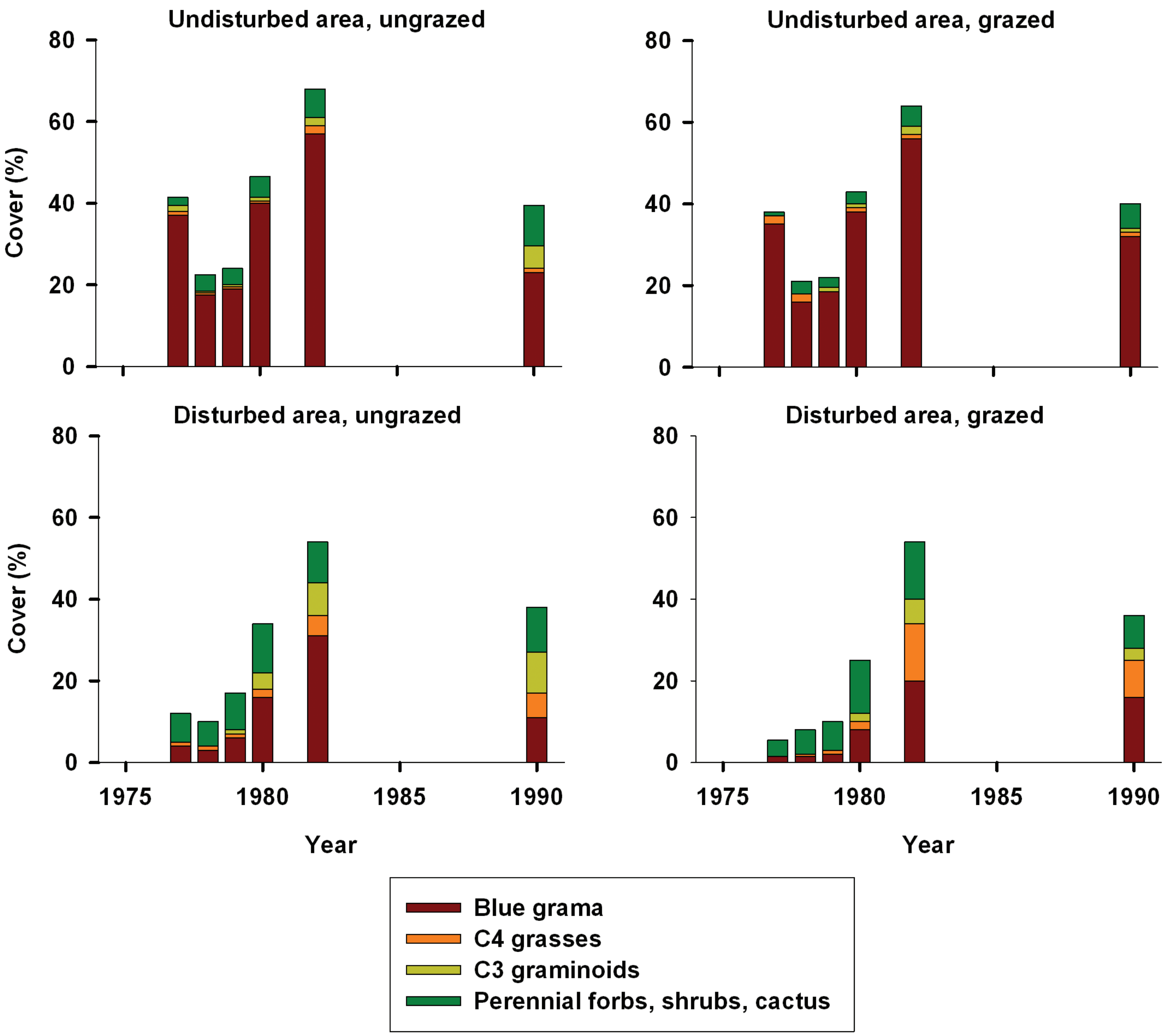


Figure 9-16. Recovery of vegetation at a shortgrass site (SGS) following plant mortality by the larvae of june beetles, a biotic disturbance, in 1977. Disturbed areas had greater percentage cover of perennial forbs and nondominant grasses compared with undisturbed areas that were primarily dominated by the warm-season perennial grass *Bouteloua gracilis* (blue grama). Areas grazed by cattle and adjacent ungrazed areas had similar patterns through time. Redrawn from Coffin et al. 1998.

A very different system, the coral reefs of French Polynesia (MCR), is experiencing a similar biotic disturbance as a result of a crown-of-thorns sea star outbreak that is killing live coral (figure 9-17). Comparison of permanent quadrats in 2006 and 2008 show the loss of coral over time. These biotic disturbances have important consequences for persistence of coral reefs, especially in combination with increasing ocean temperatures.

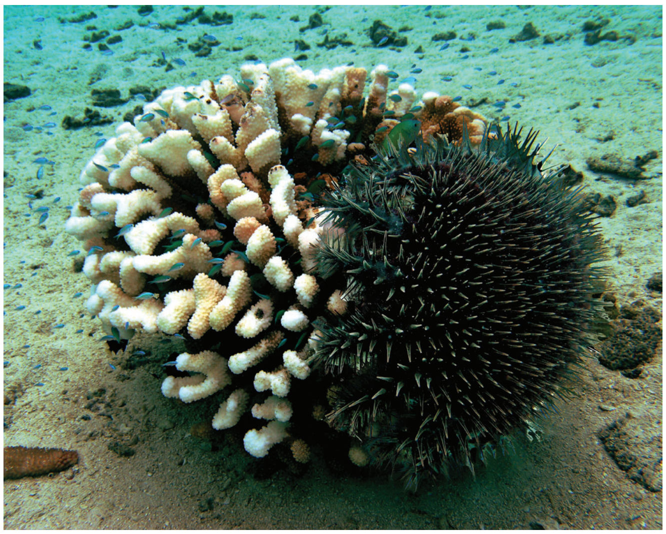


Figure 9-17. Crown-of-thorns sea star feeding on a live coral. Coral reefs of French Polynesia, Moorea Coral Reef (MCR), are experiencing a large crown-of-thorns sea star outbreak, which has decreased the cover of live coral on the reef from about 60 percent to less than 10 percent (P. Edmunds, unpublished data). Reprinted with permission from MCR.

Invasive species, either natives that expand their geographic distribution or introduced species that are transported from another region or continent, are increasingly recognized as disturbance agents. A well-documented example of the expansion of native plants is shrub encroachment into perennial grasslands in the American Southwest over the past 150 years. The expansion of shrubs is likely a result of overgrazing by livestock combined with herbivory by rabbits and extreme periodic droughts every 50-60 years. One approach to studying the recovery of perennial grasses is to remove livestock, rabbits, and shrubs from an area and then monitor vegetation as weather varies between drought and nondrought periods. In the Chihuahuan Desert, these studies show a time lag of 30-plus years before the dominant black grama responds following shrub removal; two other grass species have more variable responses (figure 9-18) (Havstad et al. 1999).

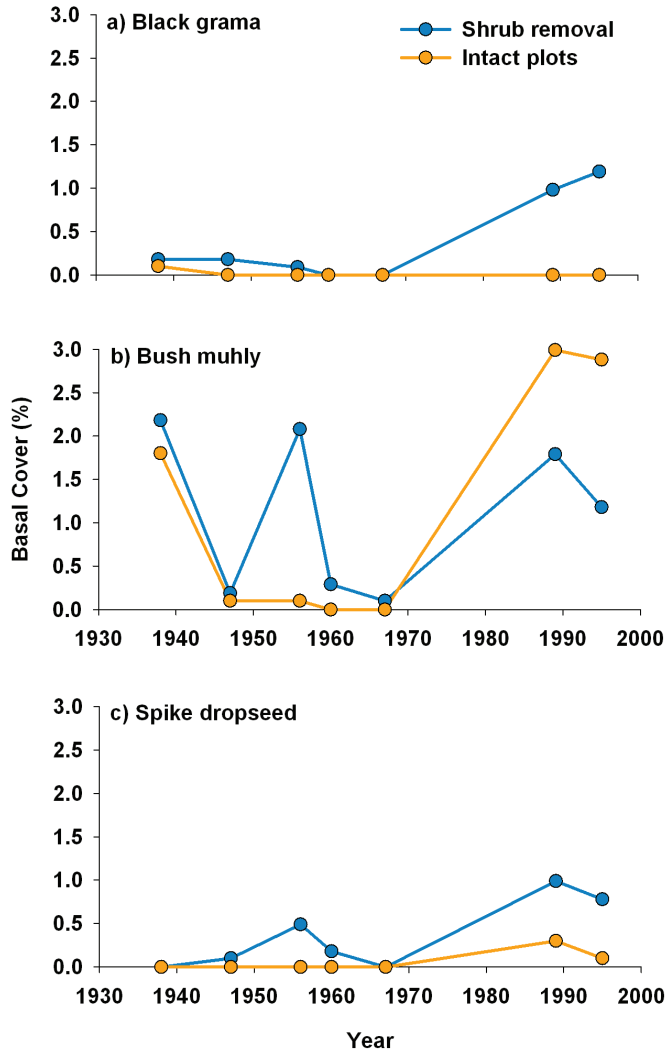


Figure 9-18. Basal cover of (a) black grama, (b) bush muhly, and (c) spike dropseed following shrub removal (blue) and on intact plots (orange) at a site in the northern Chihuahuan Desert, Jornada (JRN) (Havstad et al. 1999). Reprinted with permission from Elsevier.

Disease can make populations more vulnerable to disturbance. In the coastal bays of Virginia (VCR), populations of eelgrass *(Zostera marina)* once blanketed the seafloor and covered nearly 10,000 ha of Hog Island Bay. These populations were weakened in the early 1900s by a pandemic disease, marine slime mold "wasting disease." In 1933, a large hurricane caused local extinction of the seagrass (Orth et al. 2006). Recovery did not begin until 1998. The time lag in recovery was due to the long distance to source populations and the limited dispersal potential of seagrass seeds. Restoration efforts by seeding since 2007 have resulted in 20 hectares of expanding seagrass meadows in Hog Island Bay. Adjacent coastal bays now have 570 hectares of seagrass meadows from restoration that began in 2001.

Anthropogenic Disturbances

Human activities have direct and indirect effects on the biota (Grimm et al. 2008b). Changing land use patterns are a direct influence. In Phoenix, AZ, (CAP) the land has been converted from mostly desert and agricultural land in 1912 to mostly urban starting in 1995 (figure 9-19) (Knowles-Yánez et al. 1999). Recreational areas have also increased over the past 25 years. Similar trends in increasing urban population are seen globally (Grimm et al. 2008a) and throughout the American Southwest (figure 9-20a) (Havstad et al. 2009). Land previously valued for livestock production is now being sold for housing developments at much higher prices than their value as rangeland. The result is that livestock density has decreased since 1950 for much of this region (figure 9-20b) (Havstad et al. 2009). The consequences of shifting lifestyles on ecosystem services, such as demands for high quality and quantity of water, biodiversity, air quality, and food production, are the subject of current research in many regions of the United States (Havstad et al. 2007, Sylvester and Gutmann 2008).

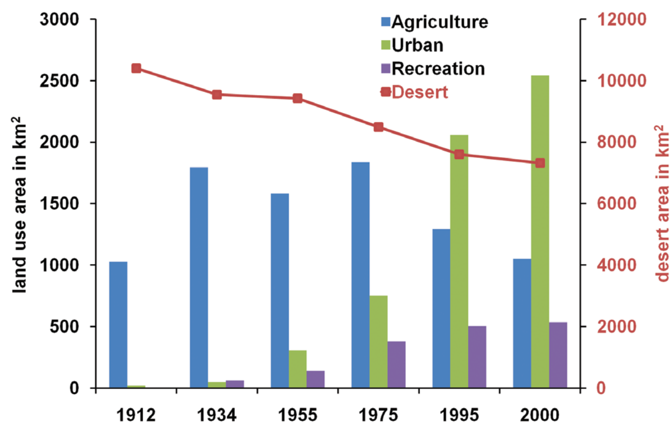


Figure 9-19. Over the past century, land in the Phoenix area, Central Arizona-Phoenix (CAP), has been converted from desert to agriculture, and ultimately to urban use. Data from Knowles-Yánez et al. (1999).

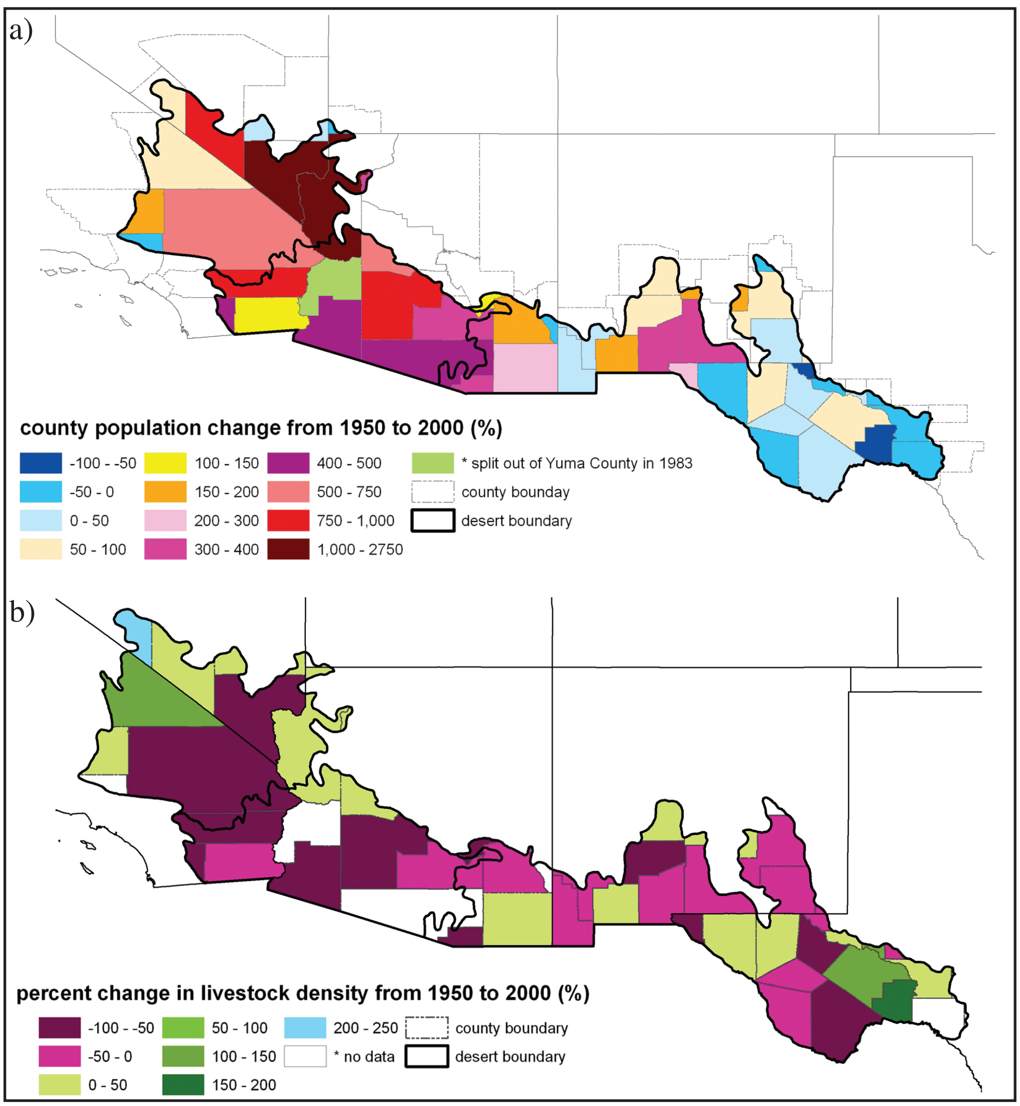


Figure 9-20. (a) Change in population as a percentage of the total from 1950 to 2000. (b) Change in livestock numbers by county for U.S. Bureau of Land Management allotments or districts between 1950 and 2000 for the United States Southwest (Havstad et al. 2009). Reprinted with permission from ASA-SSSA-CSSA.

Conclusions

Data available for a variety of sites where long-term responses to disturbance events are being monitored illustrate the complexity of these ecological phenomena. The information underscores the fact that ecosystems are continuously changing in response to complex disturbance regimes rather than to single events. Usually a particular event, such as a hurricane, fire, or species invasion, draws the attention of the public and ecologists; but invariably, when the response to the event is studied in detail, one finds that ecosystem responses are influenced by previous disturbances and interactions with others factors that make it very difficult to attribute cause and effect. Clearly, large-scale, multiple-site experiments are needed to further unravel the relationship between disturbance and ecosystem response.

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Chapter 10

Cross-Site Studies "By Design": Experiments and Observations That Provide New Insights

J. Yao, O.E. Sala, and D.P.C. Peters

In many cases, cross-site comparisons from similar experiments, often with different questions and designs, are conducted after the studies are completed to address new questions that require multiple sites. Here, we describe cross-site studies that are "by design" in which the questions, experimental layout, methods, and measurements included multiple sites from the beginning. Broad-scale questions and patterns can be addressed explicitly in these studies because the experiment or observation network was designed for comparisons among sites that are distributed spatially across one or more environmental gradients. The same design and methods of sampling allow powerful comparisons to be made without assumptions about differences in plot size, number, or sampling frequency and intensity on the results. However, these studies also have limitations:

- All sites need a similar experimental design, which can limit the types of questions that can be addressed.
- These studies typically involve large amounts of resources (time, personnel, supplies) that can limit the number of samples collected.
- Time and travel involved can also often limit graduate student involvement.
- Collaborators are needed at different sites for site selection and design details and to conduct the sampling and interpret the results.
- These studies often take longer to get started because of the coordinated efforts required by many people.

Cross-site studies are well suited to addressing large-scale questions that cannot be adequately addressed with local studies because of the uncertainties associated with extrapolation of results from one site to a much broader area. There has been a recent increase in the interest for large-scale ecological questions driven by the need to predict the consequences of global change on ecosystem functioning (IPCC 2007). Another independent demonstration of the increasing interest in regional- and continental-scale ecology is the emerging National Ecological Observatory Network (NEON) project that will be deployed throughout the continental United States (http://www.neoninc.org).

The objectives of this chapter are to present examples of the kinds of questions and results that require a priori cross-site experiments or observations and to describe new insights provided by these studies that would not have been possible with cross-site comparisons conducted from existing studies.

There are two types of cross-site studies described below: experimental manipulations of drivers or system properties and observations or monitoring of natural or managed ecosystems located along environmental gradients.

Experimental Manipulations of Ecosystems

Ongoing or Completed Cross-Site Experiments

Temperature manipulations. Global warming is occurring as a result of elevated concentrations of carbon dioxide and other greenhouse gases in the atmosphere (IPCC 2007). Regions of particular concern for increasing air temperatures are the Arctic and Antarctic, where ecosystems are dominated by cold-adapted plants and animals. The International Tundra Experiment was designed to study how ecosystems in arctic and alpine tundra respond to experimental warming (http://www.geog.ubc.ca/itex). At present, the project includes 50 sites from 13 countries (including three LTER sites) located in Antarctica (MCM), Asia, Australia, Europe, and North America (NWT, ARC). Each site follows standard protocols for experimental design. Response variables include those at the individual level (for example, height and cover of plants) and at the community level (for example, plant species richness). In one key result, canopy height and cover of deciduous shrubs and graminoids increased with elevated air temperature, and cover of mosses and lichens decreased; species richness and evenness decreased (figure 10-1) (Walker et al. 2006).

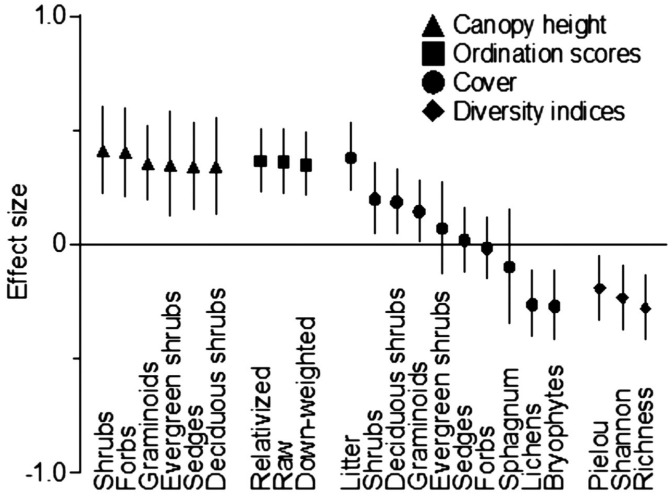

Figure 10-1. Effects of elevated air temperature on alpine and arctic tundra plants at 11 International Tundra Experiment (ITEX) sites. The mean effect size and the 95 percent confidence interval were obtained from meta-analyses of 22 variables (Walker et al. 2006). Reprinted with permission from the National Academy of Sciences, USA.

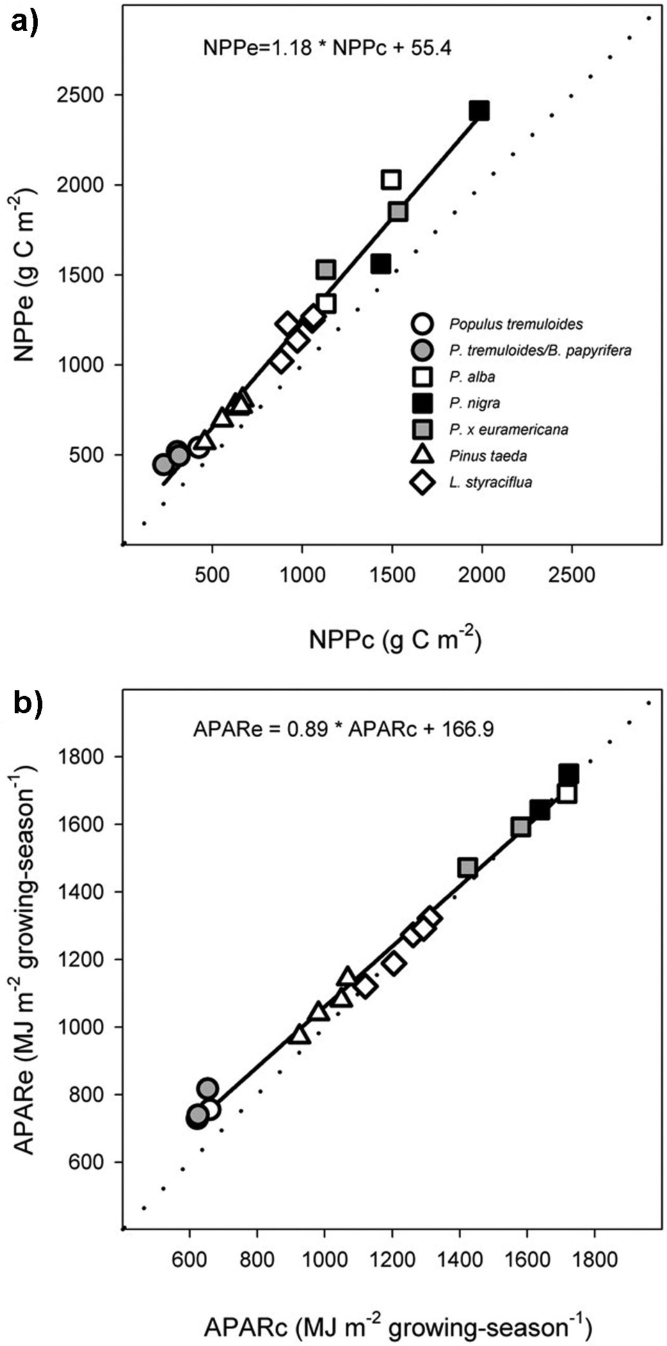

Figure 10-2. Effect of elevated CO2 concentration on forest primary production of seven species at four sites using Free Air CO_2 Enrichment (FACE) technology (Norby et al. 2005). (a) Comparison of forest net primary production at elevated (550 ppm, NPP_e) and current CO_2 concentrations (376 ppm, NPP_c). Regression: $R^2 = 0.97$, $p<0.001$, slope is significantly different from 1. (b) Comparison of absorbed photosynthetically active radiation at elevated ($APAR_e$) and current CO2 concentrations ($APAR_c$). Regression: $R^2 = 0.99$, $p<0.001$, the slope is significantly different from 1. Reprinted with permission from the National Academy of Sciences, USA.

CO_2 manipulations. Effects of increasing atmospheric carbon dioxide (CO_2) on ecosystems is being studied using the Free Air CO_2 Enrichment technology that has been adopted by 30 sites in 16 countries in Australia, Asia, Europe, and North America, including one LTER site (CDR) (http://public.ornl.gov/face/). The technology allows plant and ecosystem responses to elevated CO_2 concentration to be studied under natural conditions. Examples of response variables include plant photosynthesis and respiration and plant and soil nitrogen and carbon dynamics (Nösberger et al. 2006). Recent analyses from four sites showed that the forest's net primary production (NPP) increased at a median of 23 percent at an elevated CO_2 concentration (550 ppm) compared to forests growing under current CO_2 concentration (figure 10-2a) (Norby et al. 2005). The increase in NPP at the lower end of production was due to an increase in the ability of plants to absorb more light, as measured by Absorbed Photosynthetically Active Radiation (APAR), while the increase in NPP at the higher end was due to increase in plants' efficiency in using light (figure 10-2b).

Nutrient manipulations in streams. The Lotic Intersite Nitrogen Experiment (LINX) was designed to examine how hydrodynamic, chemical, and metabolic characteristics of streams control nitrogen uptake, retention, and cycling through the experimental addition of a stable isotope of nitrogen (^{15}N) (http://www.biol.vt.edu/faculty/webster/linx/). Ten U.S. sites participated in LINX 1 (1996 to 2001). During LINX 2 (2001-2006), effects of land use on nitrogen cycling were examined across 72 streams at 9 U.S. sites. Each site measured nitrogen uptake and denitrification rates as well as potential explanatory variables including physical, chemical, and biological characteristics of a stream and rates of stream metabolism by algae and microbes. Streams from agricultural and urban areas were found to contain higher concentrations of nitrate (NO_3^-) than streams from areas with vegetation typical of the biome (figure 10-3a) (Mulholland et al. 2008). The rates of total biotic nitrate uptake, one of two ways of nitrogen removal in streams, were higher in streams from agricultural and urban areas (figure 10-3b), stimulated by the increased nitrate concentrations. However, the nitrate uptake efficiency decreased with increasing nitrate concentration.

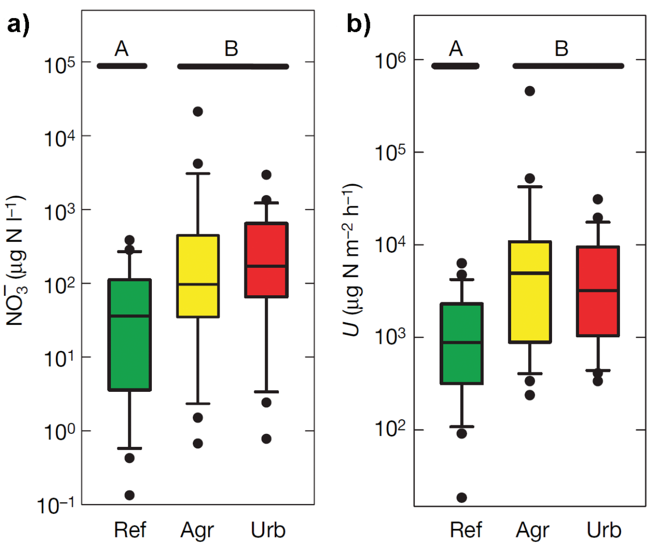

Figure 10-3. Nitrogen in streams located in different areas in the LINX2 project (Mulholland et al. 2008). (a) Nitrate (NO_3^-) concentration. (b) Total biotic nitrate uptake rate. Ref: streams in areas with vegetations typical of the biome; Agr: streams adjacent to agricultural practices; Urb: streams in urban areas. Reprinted with permission from Macmillan Publishers Ltd.

Animal removal. Removal of animals combined with monitoring of environmental variables has been used to investigate interactions among components of ecosystems that show similarities across sites. For example, results of removing seed-eating rodents or ants from desert shrublands were compared with removal of insect herbivores in a tree-dominated system (Brown et al. 2001). Each system was monitored for over 20 years; data recorded included variable precipitation. In the desert site (Portal, AZ), interactions were found among precipitation, food supply, and rodent populations. At the forest site (Sunset Crater, AZ), complex dynamics emerged from the interactions among abiotic stress, dominant tree growth and morality, keystone herbivores, and other trophic levels (Brown et al. 2001).

These results were used as the basis for an ongoing study at three sites in the Chihuahuan Desert: Sevilleta LTER (SEV), Jornada Basin LTER (JRN), and Mapimi Biosphere Reserve near Durango, Mexico (D.C. Lightfoot, unpublished data). The project was initiated in 1993 to experimentally determine how small mammals affect Chihuahuan Desert ecosystems, either grasslands or shrublands, and how small mammals are affected by climate change (http://tierra.unm.edu/projects/chihuahuan-desert-small-mammal-exclosure).

Litter manipulation. Litter decomposition is an important ecosystem process in which biochemical molecules in plants are broken down by microorganisms and made available in simpler forms for uptake by other organisms. The Long-Term Intersite Decomposition Experiment Team (LIDET) studied the effects of substrate quality (species and type of litter) and climate on long-term decomposition and nitrogen accumulation in litter (http://andrewsforest.oregonstate.edu/research/intersite/lidet.htm). Twenty-eight sites from seven biomes, including 15 LTER sites, followed the same methods. Response variables included litter mass, total nitrogen, lignin, and cellulose in material remaining in litter bags. Results during a 10-year period found that net nitrogen immobilization and release from leaf litter in six of the seven biomes depended strongly on initial nitrogen concentration in litter but did not depend on climate, other litter qualities, or local site characteristics (Parton et al. 2007). At high initial nitrogen concentration in leaf litter (1.98 percent), net nitrogen immobilization was close to 0; nitrogen release started when about 60 percent of the mass remained in a litter bag (figure 10-4a). At low initial nitrogen concentration (less than 0.39 percent), net nitrogen immobilization was high, and nitrogen release started when about 40 percent of the mass remained in a litter bag (figure 10-4d).

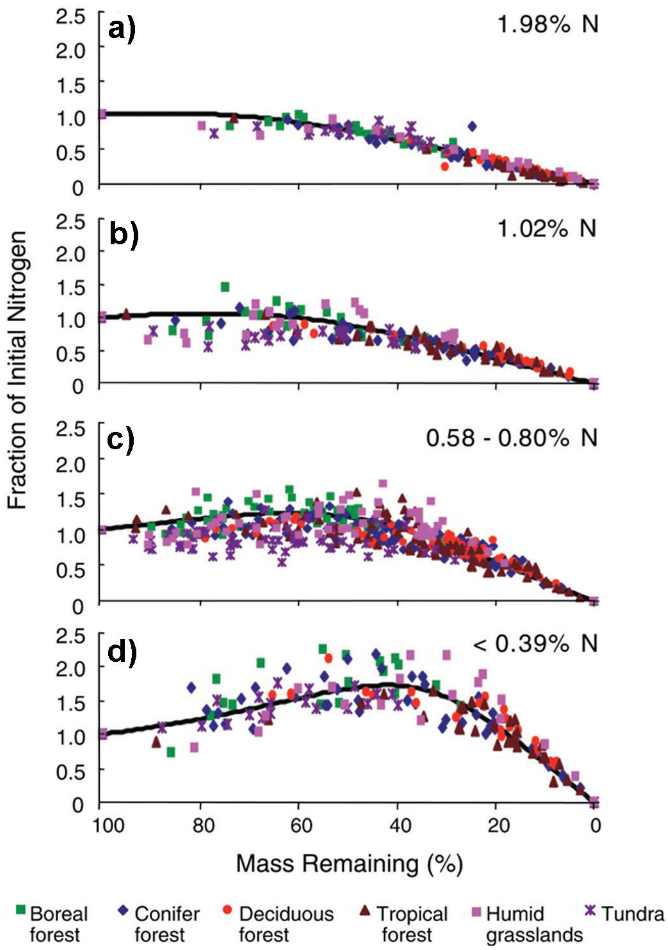

Figure 10-4. Pattern of nitrogen (N) immobilization and release from the LIDET study depends on the initial N concentration of leaf litter, shown as percentage in the upper right corner of each panel (Parton et al. 2007). N immobilization refers to the conversion of N from inorganic (usable by plants and microbes) to organic form (not usable). N release refers to the conversion of N from organic to inorganic form. Values of fraction of initial N > 1 indicate N immobilization while values < 1 indicate N release. Reprinted with permission from AAAS.

Biodiversity manipulations. Long-term studies that manipulated species richness in grasslands at the CDR LTER site found that aboveground net primary productivity (ANPP) and biomass increase as species richness (biodiversity) increases (Tilman et al. 1997, 2001, Reich et al. 2004, Fargione et al. 2007, Fornara and Tilman 2009). Similar biodiversity manipulations were conducted in Europe for eight sites in the Biodiversity and Ecological Processes in Terrestrial Herbaceous Ecosystems (BIODEPTH) project. Results confirmed the patterns found at CDR: ANPP increased as plant species richness increased at seven sites. The effect of biodiversity on production became stronger over time at most sites (Hector et al. 1999, Spehn et al. 2005). However, comparisons across ecosystem types have shown that the relationship between productivity and richness can take a variety of forms (Mittelbach et al. 2001).

New or Developing Cross-Site Experiments

Nutrient additions in grasslands. Nutrient Network is being designed to study the effects of nutrient (nitrogen, phosphorus, and potassium) additions in grasslands (http://nutnet.science.oregonstate.edu/). The research questions are:

- How general is current understanding of productivity-diversity relationships?
- To what extent are plant production and diversity co-limited by multiple nutrients in herbaceous-dominated communities?
- Under what conditions do grazers or fertilization control plant biomass, diversity, and composition?

All sites follow the same experimental protocol and collect similar data (Adler et al. 2011). The project started in 2009 with 52 sites in eight countries in Africa, Asia, Australia, Europe, and North America, including six LTER sites (AND, CDR, KNZ, NWT, SEV, SGS).

Anthropogenic manipulations in streams. A stream experimental and observational network (STREON) is part of the emerging NEON program. This study is expected to examine effects of nutrient loading, species losses, and hydrologic change on the structure and functioning of streams (http://www.neoninc.org/science/experiments). All sites will follow the same experimental protocols. Natural hydrologic events (flood and drought) will be recorded. Biological variables and other variables related to material flux and rates of nutrient transformations and metabolism are expected to be measured (Dodds 2008).

Rainfall manipulations. Rainfall is the most important determinant of ANPP in grasslands, steppes, and deserts (Sala et al. 1988). Manipulations of rainfall are often used to study how systems may respond in the future under altered rainfall regimes (IPCC 2007). Most rainfall manipulations require expensive installations that constrain the spatial extent of the manipulation, the number of replications, and the power of the experimental design (Hanson 2000). An inexpensive rainout shelter design (Yahdjian and Sala 2002) has recently been adopted in many locations around the world, from South Africa and Patagonia to the Alaskan Tundra (figure 10-5), including three LTER sites (JRN, SGS, ARC). These experiments use the same method to manipulate incoming precipitation, although there is not a formal network of rainfall manipulations. Future synthesis of results is expected to provide unique insights into the response of ecosystems to water availability along gradients of temperature and precipitation.

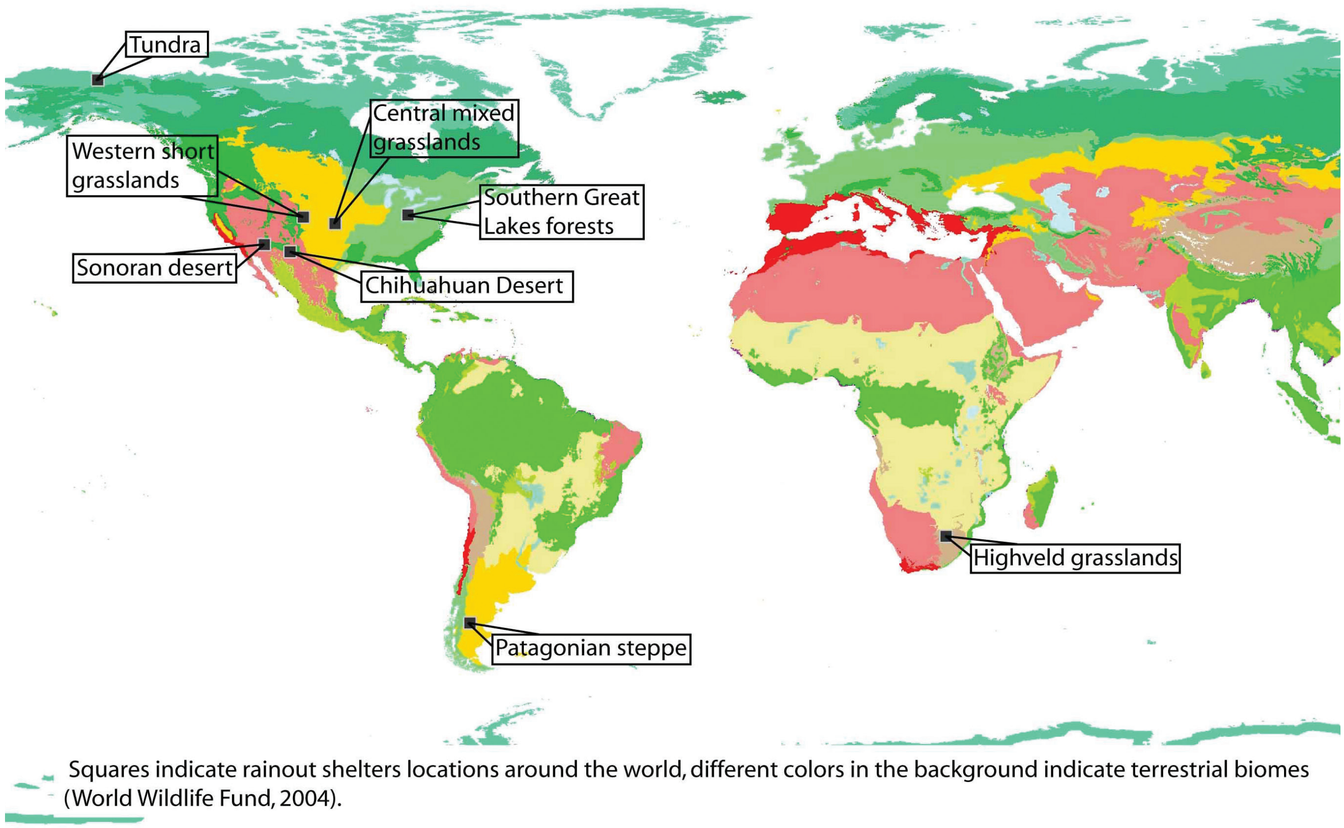

Figure 10-5. Sites using the rainout shelter design of Yahdjian and Sala (2002).

Monitoring of Ecosystems

Ongoing Monitoring Networks

Observations of the environment, such as climate (http://www.ncdc.noaa.gov), atmospheric chemistry (http://nadp.sws.uiuc.edu/NADP/), and human populations (http://census.gov) have been made in the United States over the past century or longer. Data from these networks form the basis for cross-site comparisons in chapters 11 to 14. Here we focus on networks of sites collecting information about ecosystem dynamics in response to these environmental and human drivers.

Carbon dioxide and water vapor fluxes. Two existing networks of sites are collecting data on carbon, water, and energy fluxes. The two networks use different technology to address similar questions.

The Rangeland Carbon Dioxide Flux Project is examining the effect of management practices on the global carbon balance for eight U.S. sites (including one ARS-LTER site: JRN) (Svejcar et al. 1997). The Bowen ratio-energy balance system is being used to measure energy, water vapor, and carbon dioxide fluxes. An analysis of net ecosystem exchange of carbon during 1996-2001 showed that five sites are sinks for atmospheric CO_2 (figure 10-6) (Svejcar et al. 2008). The three sites that are sources of atmospheric CO_2 are in the Great Plains and Southwestern deserts of the United States.

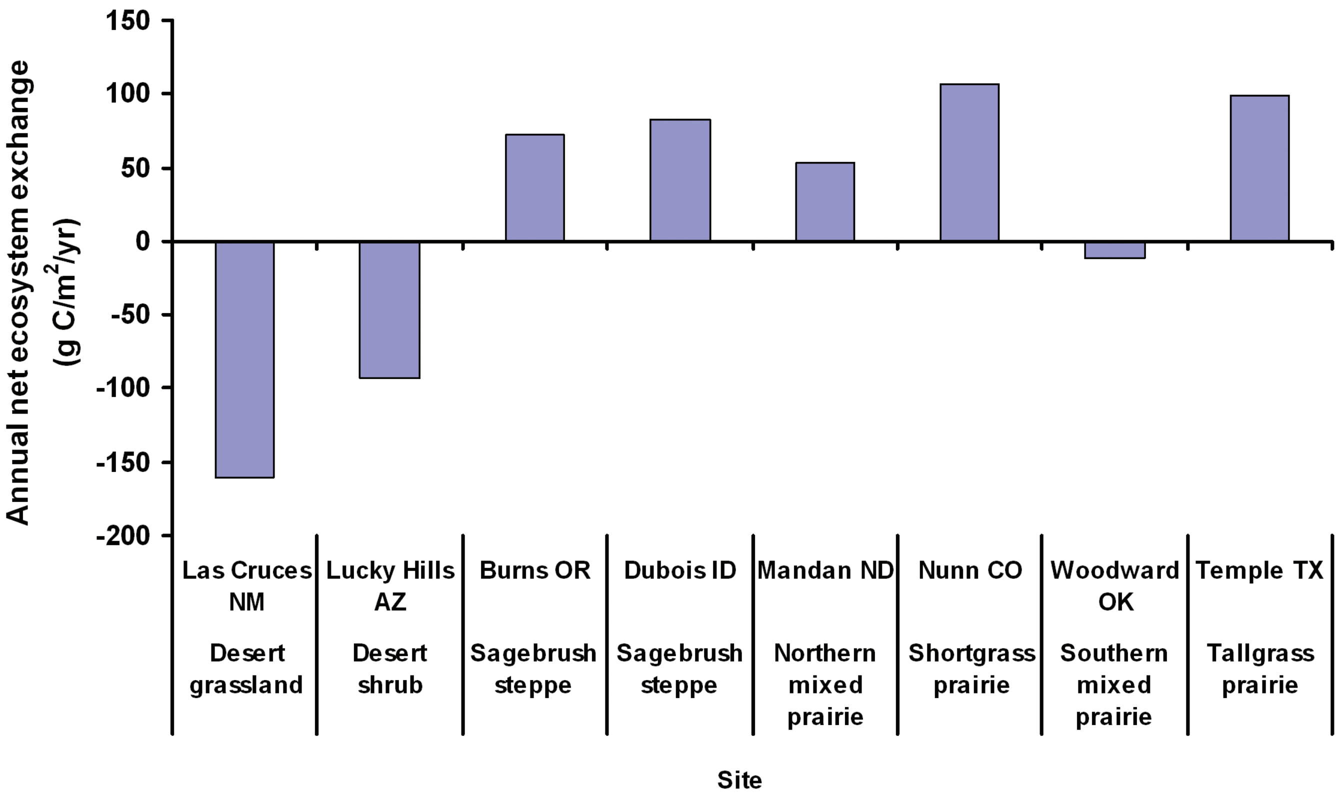

Figure 10-6. Average annual net ecosystem exchange of carbon (g/m/yr) at eight sites from the rangeland carbon dioxide flux project. Sites with positive values are carbon sinks because carbon accumulates in vegetation and soil. Sites with negative values are sources of atmospheric carbon dioxide because carbon is released into the atmosphere. Two ARS-LTER sites are included: desert grassland (JRN) and shortgrass prairie (SGS). Data from Svejcar et al. (2008).

FLUXNET is a network of regional networks monitoring carbon dioxide and water vapor fluxes in terrestrial ecosystems using eddy covariance towers, an alternative approach to Bowen ratio systems (http://www.fluxnet.ornl.gov/fluxnet/). The goals are to characterize spatial and temporal variation in CO_2 and water vapor fluxes and to understand the drivers causing this variation. Started in the 1990s, currently more than 500 sites in Africa, Asia, Australia, Europe, and North and South America participate. Variables related to vegetation, soil, hydrology, and meteorology are collected. The first global standardized dataset was established in 2007 (http://www.fluxdata.org/).

The AmeriFlux network, started in 1996, is a network within FLUXNET (http://public.ornl.gov/ameriflux/). Its research questions are—

- What are the magnitudes of carbon storage and the exchanges of energy, CO_2, and water vapor in terrestrial systems? What are the spatial and temporal variability?
- How is this variability influenced by vegetation type, phenology, land use change, management, and disturbance history, and what is the relative effect of these factors?
- What is the causal link between climate and the exchanges of energy, CO_2, and water vapor for major vegetation types? How do seasonal and interannual climate variability and anomalies influence fluxes?
- What is the spatial and temporal variation of boundary layer CO_2 concentrations, and how does this vary with topography, climatic zone, and vegetation?

Currently the AmeriFlux network consists of 133 sites in 5 countries in North and South America.

New or Developing Monitoring Networks

A number of observational networks have emerged over the past decade to collect similar ecological data from a number of sites (Peters et al. 2008). Existing or emerging networks funded at least in part by the National Science Foundation to collect ecologically relevant data from U.S. sites include the Ocean Observatories Initiative (OOI; http://www.oceanleadership.org/programs-and-partnerships/ocean-observing/ooi/), WATERS Network (http://www.watersnet.org), the Arctic Observing Network (AON; http://www.arcus.org/search/aon.html), the Global Lakes Ecological Observatory Network (GLEON; http://www.gleon.org/), and the National Phenology Network (http://www.usanpn.org/). Here we describe in more detail two networks that include a number of LTER sites, NEON and the Microbial Inventory Research Across Diverse Aquatic (MIRADA) LTERs.

NEON is being designed to study the effects of land use, climate change, and invasive species on structure and functioning of ecosystems in the United States (http://www.neoninc.org/). Observational data will be collected from sites selected to represent one of 20 eco-climatic domains based on vegetation, landform, and climate. All sites will follow the same sampling protocols and collect the same core data, expected to include biological, hydrological, and atmospheric variables (Keller et al. 2008). NEON sites will also use eddy covariance towers to study carbon, water, and energy fluxes, similar to the AmeriFlux network.

The MIRADA LTERs started in 2007 with the goal of building an inventory of microbial operational taxonomic units in marine and freshwater ecosystems (http://amarallab.mbl.edu/mirada/). Both diversity and relative abundance of microbes will be documented, and the physical and chemical drivers behind the observed patterns of microbial diversity will be studied. The project includes 13 LTER sites that study aquatic ecosystems. All sites use a standardized gene sequencing protocol.

Summary

This chapter has presented examples of cross-site experimental manipulations and observations that have yielded unique and extraordinary results. Insights resulting from these cross-site experiments could not have been obtained with another approach. Cross-site experiments allow scientists to address large-scale questions and to isolate cause-and-effect relationships, which are more difficult in observational studies. The importance of large-scale studies across sites has grown in the last decade as society has recognized the need to understand the phenomenon of global change and to predict its impacts on ecosystems and society (MEA 2005). Global change is a large-scale phenomenon that demands studies at this scale (IPCC 2007). However, not all studies can be done at a large scale. For example, elevated carbon dioxide studies can be done only in small plots. Replication across sites provides the means to address differential responses that occur at large scales.

Cross-site experimentation is an ideal tool to address novel and urgent questions, yet this approach faces some difficulties. Costs are usually higher than standard experiments and require major investments in coordination. In addition, funding opportunities for cross-site experimentation are scarce compared with standard grants. Funding agencies and the academic community may need to modify their approaches to allow for this new type of research tool to flourish and yield the results that society demands.

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Chapter 11

Long-Term Trends in Climate and Climate-Related Drivers

In this chapter, we first describe common methods to measure climate and climate-related drivers and our rationale for the selection of variables in this book. We then show graphs of climate data through time for each site and summary maps at the continental scale.

Methods of Measurements and Selection of Variables

Climate has been monitored throughout the United States since President Grant started the National Weather Service in 1870. Numerous standardized measurement locations exist on land, in streams and lakes, and in the coastal ocean. In this report, we focus on contemporary climate records (late 1880s to present) obtained from standardized instruments and stations located at or near the research sites described in this book.

For land sites, standardized data were obtained from meteorological stations either located and maintained at a research site or at a nearby airport or city and maintained, in most cases, by the National Weather Service (NWS) and archived by the National Climate Data Center. The NWS station at the nearest city was used for coastal sites. For terrestrial sites, the onsite station was used unless a longer record was available from a nearby NWS station with similar climate. In some cases, we used onsite data combined with NWS data to obtain a longer-term weather record.

Standards are used at all sites for daily measurements of minimum and maximum air temperature (°C), precipitation (mm), relative humidity (%), wind speed (m/sec) and direction (from 0 to 360°), and solar radiation (MJ/m^2) (WMO 2008). Other measurements, such as soil temperature (°C) and soil moisture (% or cm water per cm soil) often have site-specific criteria for depth and timing that make cross-site comparisons difficult. Here, we show climate data for all 50 sites for four variables most commonly used by ecologists (minimum, maximum, and average air temperature, and precipitation) (Greenland 1986). For each variable, we calculated the mean across all days in each year of the record to focus on long-term trends in annual values. Data for climate variables can be found on the Internet, either on individual research site home pages or on the EcoTrends website (http://www.ecotrends.info).

We show two additional measures of climate that are particularly useful in comparing ecosystems. First, the Palmer Drought Severity Index (PDSI) was obtained for all sites where calculations are available (http://www7.ncdc.noaa.gov/CDO/cdo); this analysis excludes sites in Alaska, Antarctica, French Polynesia, and Puerto Rico. This index uses air temperature and rainfall information as well as soil properties to estimate monthly moisture supply and demand as a measure of departure from the mean condition at a site (Palmer 1965, Heim 2002). The PDSI is standardized to local climate to allow sites to be compared for relative drought or rainfall conditions. A value of 0 is normal; drought is shown by negative numbers. Drought severity increases with the absolute value of the negative number (-3 is moderate drought; -4 is extreme drought). Excess rain is shown by the magnitude of the positive number (for example, 2 is moderate rainfall). Second, we calculated Walter-Lieth climate diagrams for each site using monthly total precipitation and average air temperature values, scaled two to one respectively. These diagrams allow climate seasonality to be compared among sites using standardized diagrams. Shading of the diagrams are used to illustrate dry or wet months (see figure 11-1).

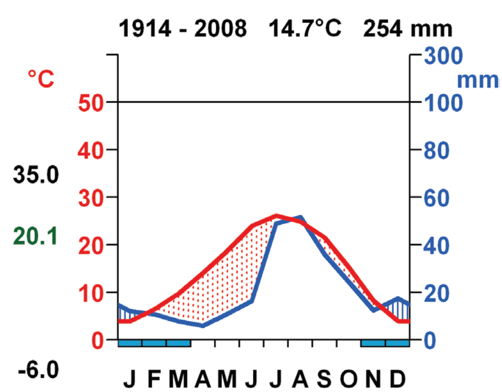


Figure 11-1. Example of a Walter-Lieth climate diagram for one site, Jornada (JRN). Mean monthly temperature in degrees Celsius (left axis, red) is plotted with precipitation in millimeters (right axis, blue) for each month in the year (bottom axis, J-D = January-December). Areas shaded in speckled red indicate dry months; areas with blue vertical lines indicate wet months. Dark blue bars at the bottom of the diagram indicate months with possible frost. The title gives range of years the data fall within, the average annual temperature, and the average annual precipitation. Black and green numbers on the left axis, from top to bottom, are the mean maximum temperature of the hottest month (black), the mean daily temperature range (green), and the mean minimum temperature of the coldest month (black), respectively.

In water, five common measurements are illustrated. Streamflow is measured daily in liters per second by gauges located within streams using standards determined by the U.S. Geological Survey (Buchanan and Somers 1969). Sea level (meters), as shown here, is measured in coastal oceans using tide gauges that measure sea surface height relative to a nearby geodetic benchmark. Ice duration is the number of days in a year on which a lake is ice covered. Water clarity or transparency is measured using a Secchi disk in oceans and lakes (Hutchinson 1957). A circular disk mounted on a line is lowered slowly in the water, and the depth at which the pattern on the disk is no longer visible is the Secchi depth (meters), which is proportional to the average light extinction coefficient. Standard methods for lake monitoring are available from the U.S. Environmental Protection Agency (http://www.epa.gov/OWOW/monitoring). Water temperature (^{o}C) is measured at a near-surface depth in streams, lakes, and oceans using thermometry or temperature probes.

Graphs Showing Long-Term Trends

The remainder of this chapter is devoted to showing trends in climate and climate-related drivers displayed in two ways to provide a sense of change across a range of spatial scales (continent, site) for each variable. First, we provide a summary of trends at the continental scale using maps that show either the mean across years or the slope of the regression line (if significant) across time for each of four variables collected at all sites (precipitation and minimum, average, and maximum air temperature). Slopes are shown using either red (positive) or blue (negative) bars; the height of the bar is the magnitude of the slope. Following the continental-scale maps for precipitation and temperature, we show site-scale data through time using four panels: (1) annual average minimum, mean, and maximum air temperature, (2) annual precipitation, (3) annual PDSI, and (4) monthly average air temperature and precipitation in a Walter-Lieth diagram. For panels 1 and 2, a solid line indicates a significant positive or negative trend through time ($p \leq 0.05$) based on simple linear regression, uncorrected for autocorrelation. The site graphs are organized by ecosystem type to allow comparisons of sites in the same ecosystem. Five additional variables are shown for sites where these data are collected: ice duration, sea level, streamflow, water clarity (Secchi depth), and surface water temperature. For variables with many sites (sea level height, streamflow), continental-scale maps of averages and slopes are shown. For all five variables, site-scale graphs through time are embedded within a continental map, and the same regression statistics are shown as in the previous panels. Long-term means and regression coefficients can be found in appendices 2 through 4.

Summary

A few noteworthy trends can be seen in these graphs. Air temperatures are increasing in at least one variable (minimum, mean, maximum) for 27 of the 50 sites. Although effects of global warming may be most dramatic and most visible to the public at high latitudes in the Arctic and Antarctic, much of North America is experiencing increases in air temperatures. In addition, sea level is increasing at all 11 coastal sites. This combination of increasing global change drivers (air and water temperature, sea level) can be expected to have more serious ecological impacts than individual drivers acting alone. Coastal waters and lakes may be susceptible to factors that increase water temperature: Increases in water temperature at three sites (CCE, SBC, and NTL) were not found in water bodies in other parts of the country or at high latitudes. Additional sites would have to be sampled to confirm this spatial pattern. Observing these trends in climate across multiple ecosystems across continents is only possible with spatially extensive, long-term data collection and analysis, such as provided by the EcoTrends Project.

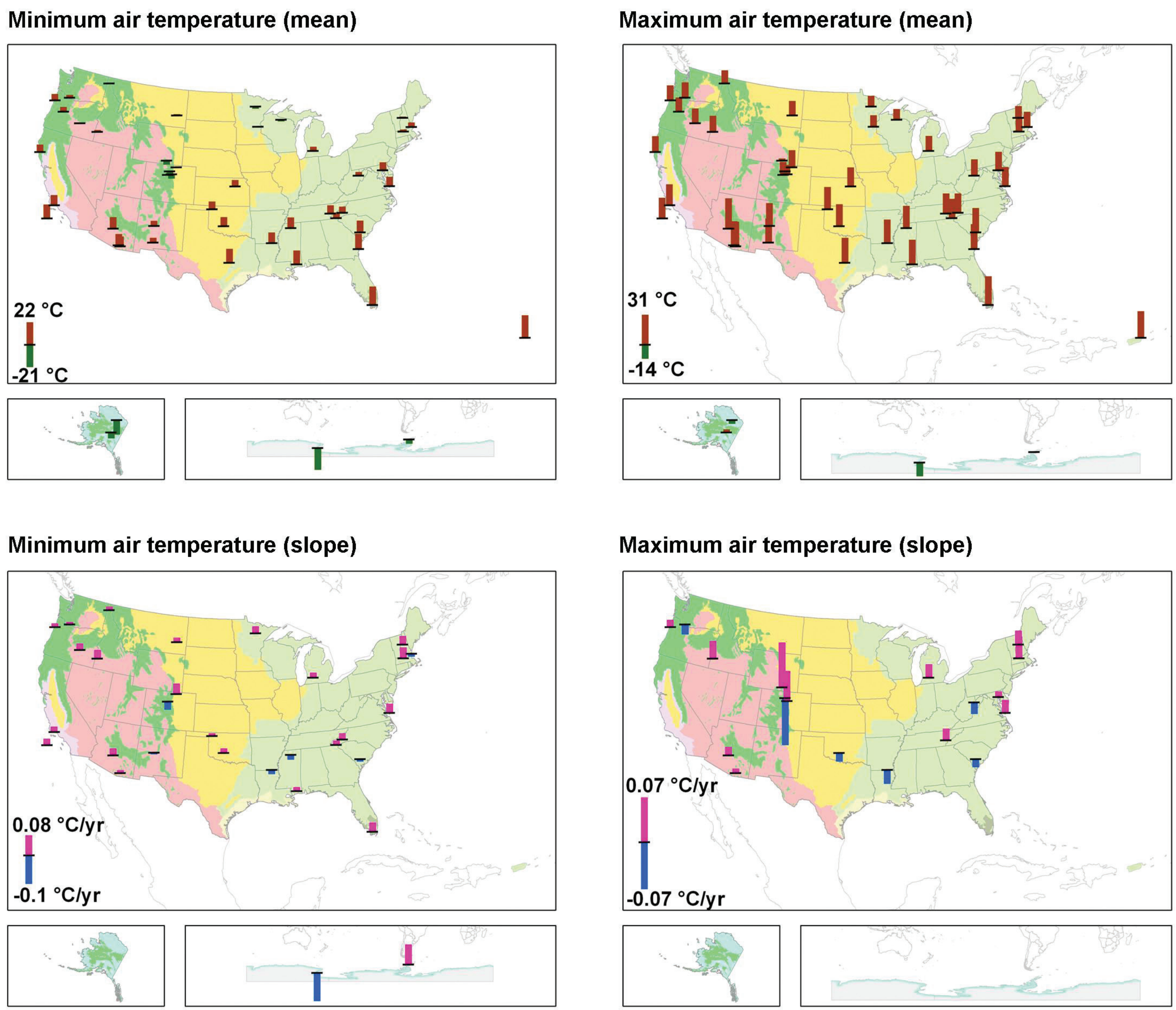


Figure 11-2. Top panels: continental patterns of long-term average annual minimum and maximum air temperature (°C) for all sites. (Positive values are red; negative values are green.) Bottom panels: slopes of significant regression lines ($p < 0.05$). (Positive values are pink; negative values are blue.) Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

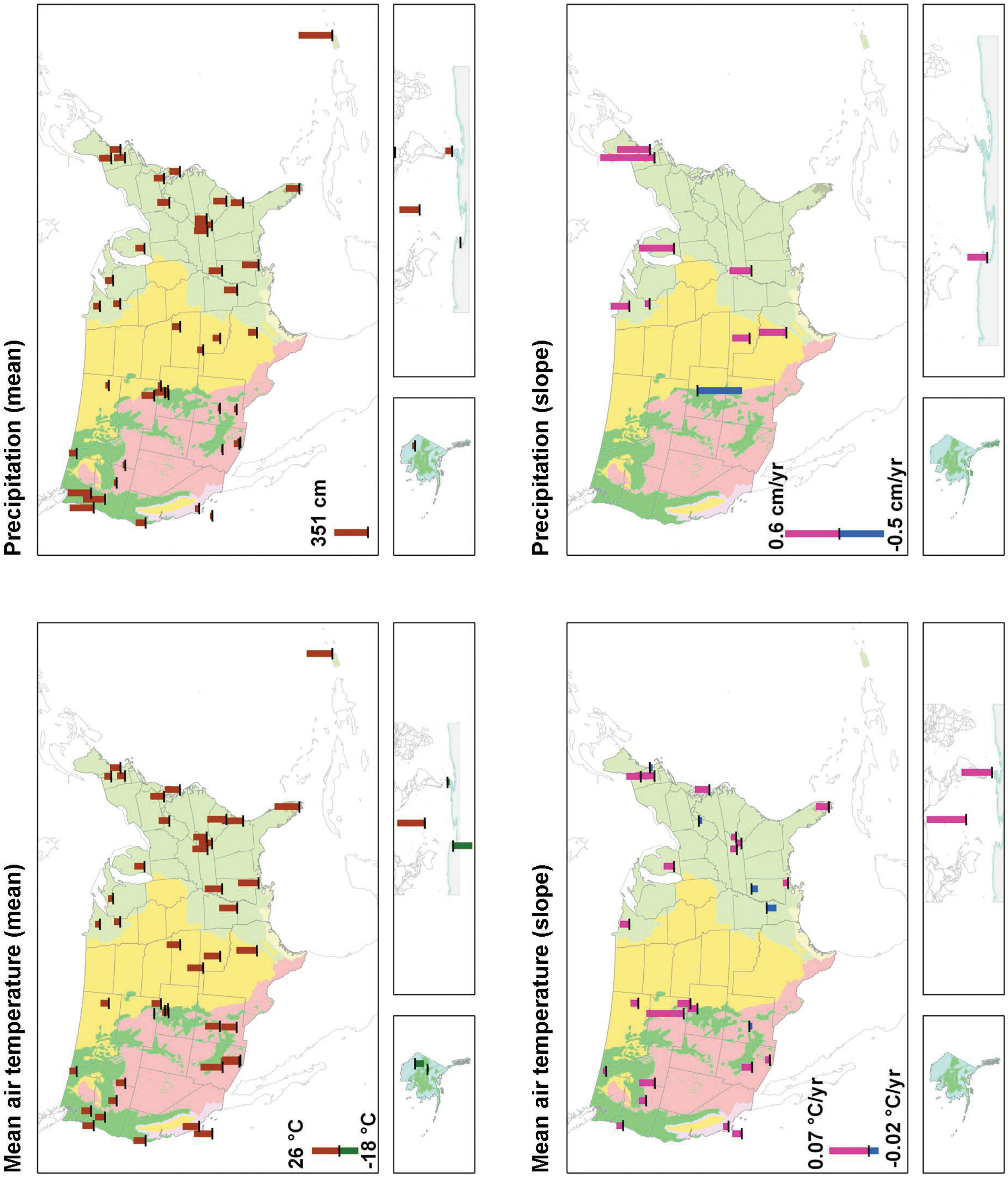


Figure 11-3. Top panels: continental patterns of long-term average annual mean air temperature (°C) and annual precipitation (cm) for all sites. (Positive values are red; negative values are green). Bottom panels: slopes of significant regression lines ($p < 0.05$). (Positive values are pink; negative values are blue.) Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

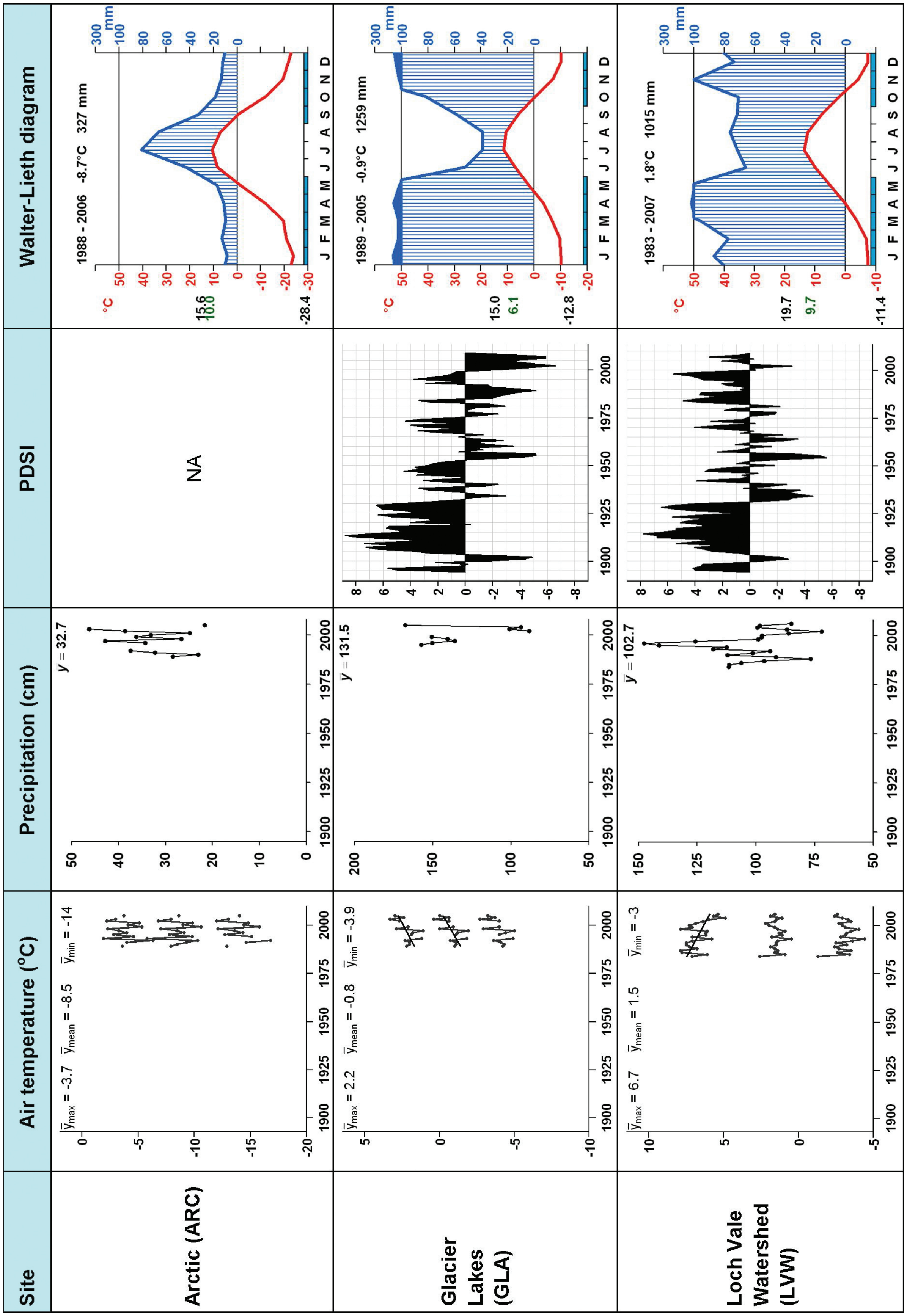


Figure 11-4 (Alpine and Arctic sites) continued next page.

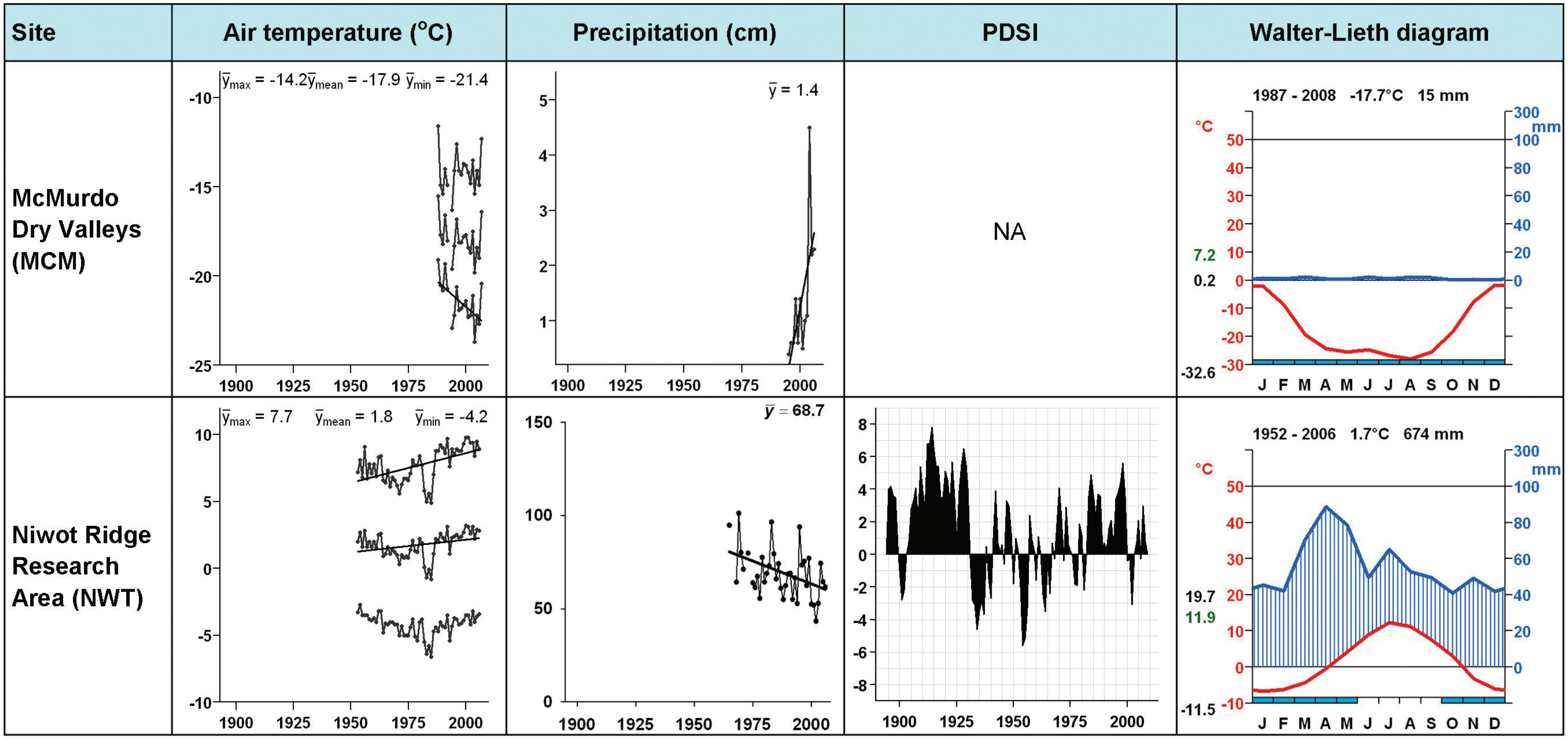


Figure 11-4. Trends for each alpine and arctic site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NS = non-significant) Arctic (ARC): NS, NS, NS, NS; Glacier Lakes (GLA): NS, 0.071, 0.066, NS; Loch Vale Watershed (LVW): NS, NS, -0.069, NS; McMurdo Dry Valleys (MCM): -0.114, NS, NS, 0.215; and Niwot Ridge Research Area (NWT): NS, 0.019, 0.044, -0.490. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

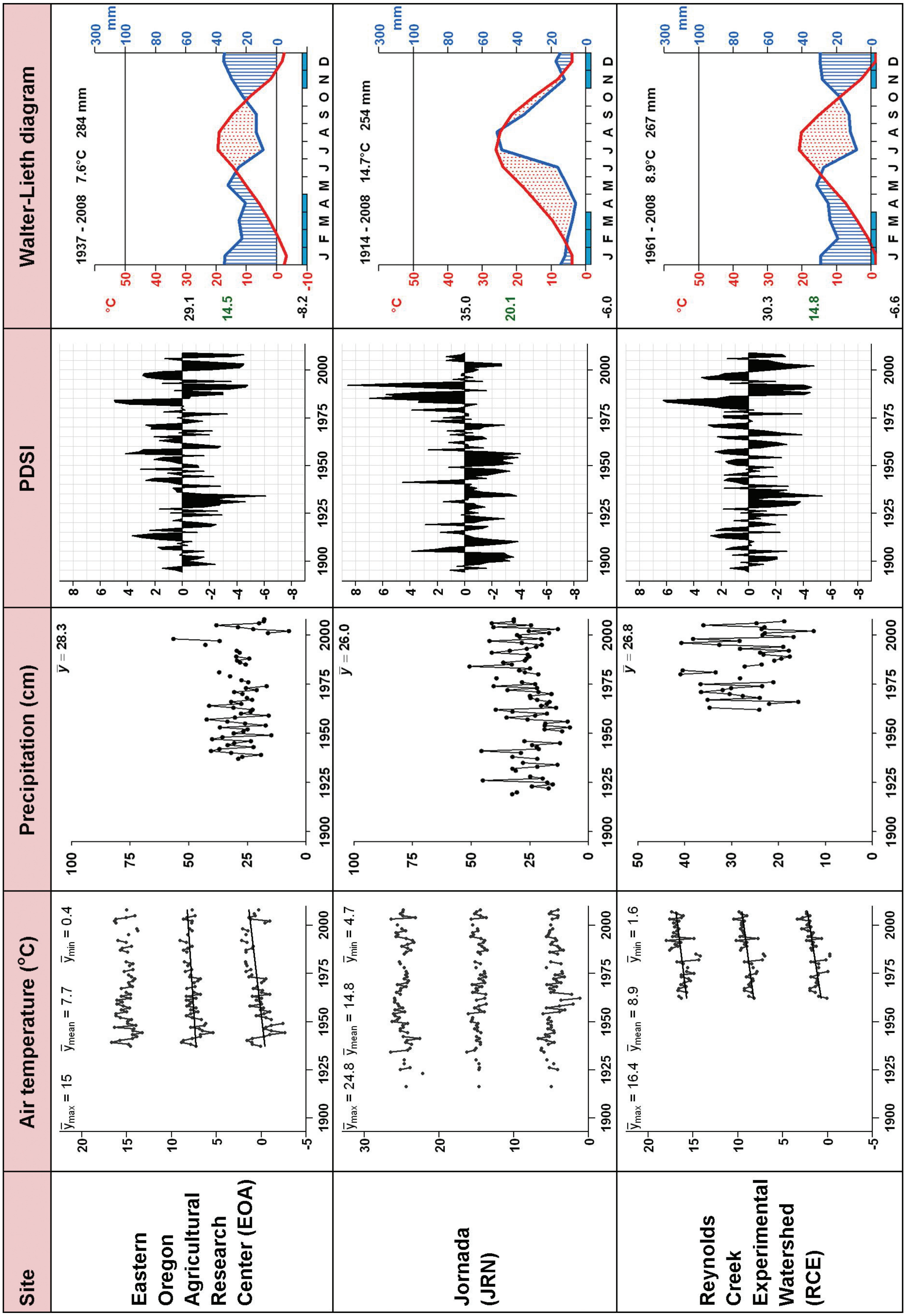


Figure 11-5 (aridland sites) continued next page.

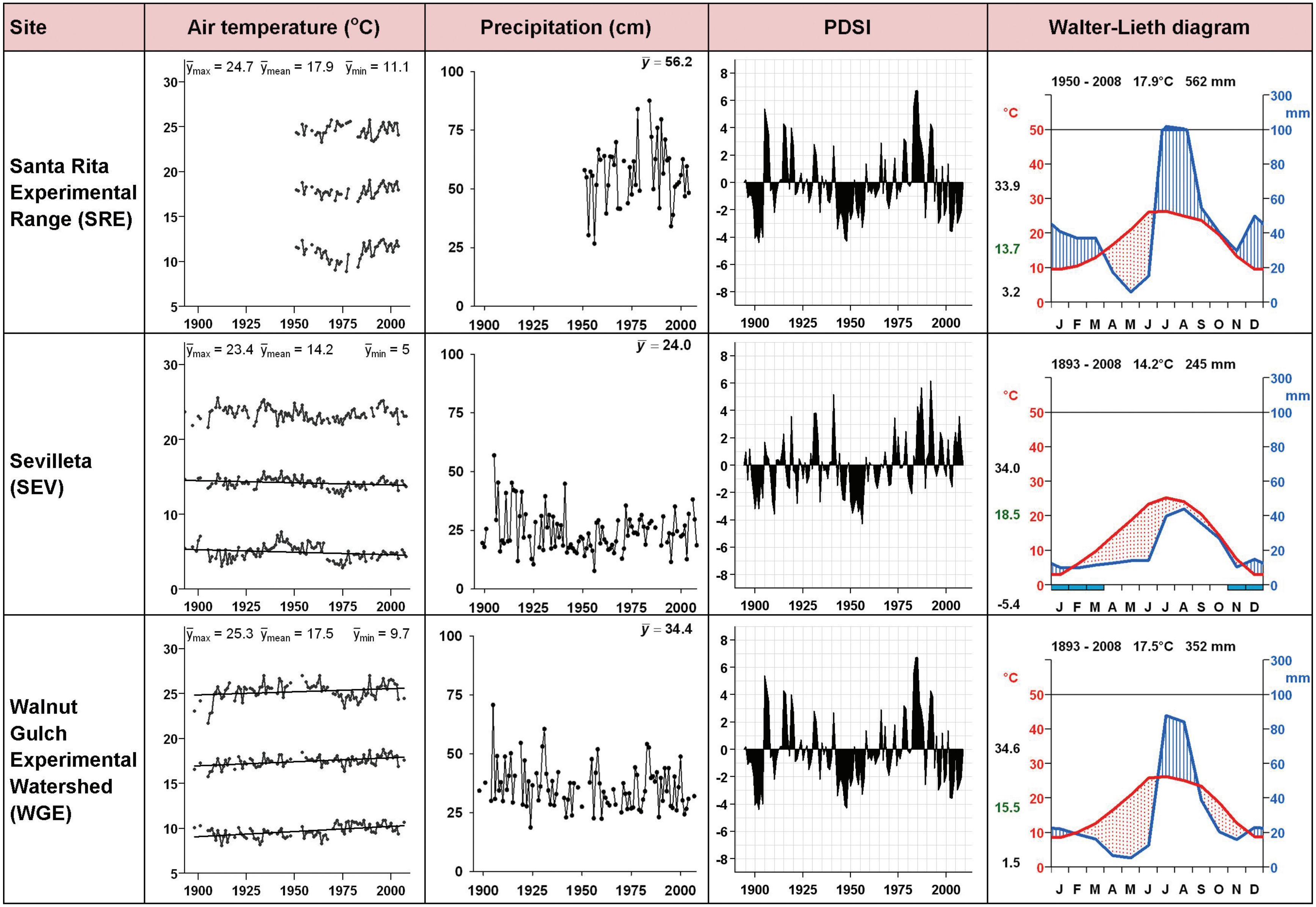


Figure 11-5. Trends for each aridland site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NS = non-significant) Eastern Oregon Agricultural Research Center (EOA): 0.025, 0.014, NS, NS; Jornada (JRN): NS, NS, NS, NS; Reynolds Creek Experimental (RCE): 0.034, 0.030, 0.026, NS; Sevilleta (SEV): -0.006, -0.006, NS, NS; Santa Rita Experimental Range (SRE): NS, NS, NS, NS; and Walnut Gulch Experimental (WGE): 0.011, 0.009, 0.007, NS. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

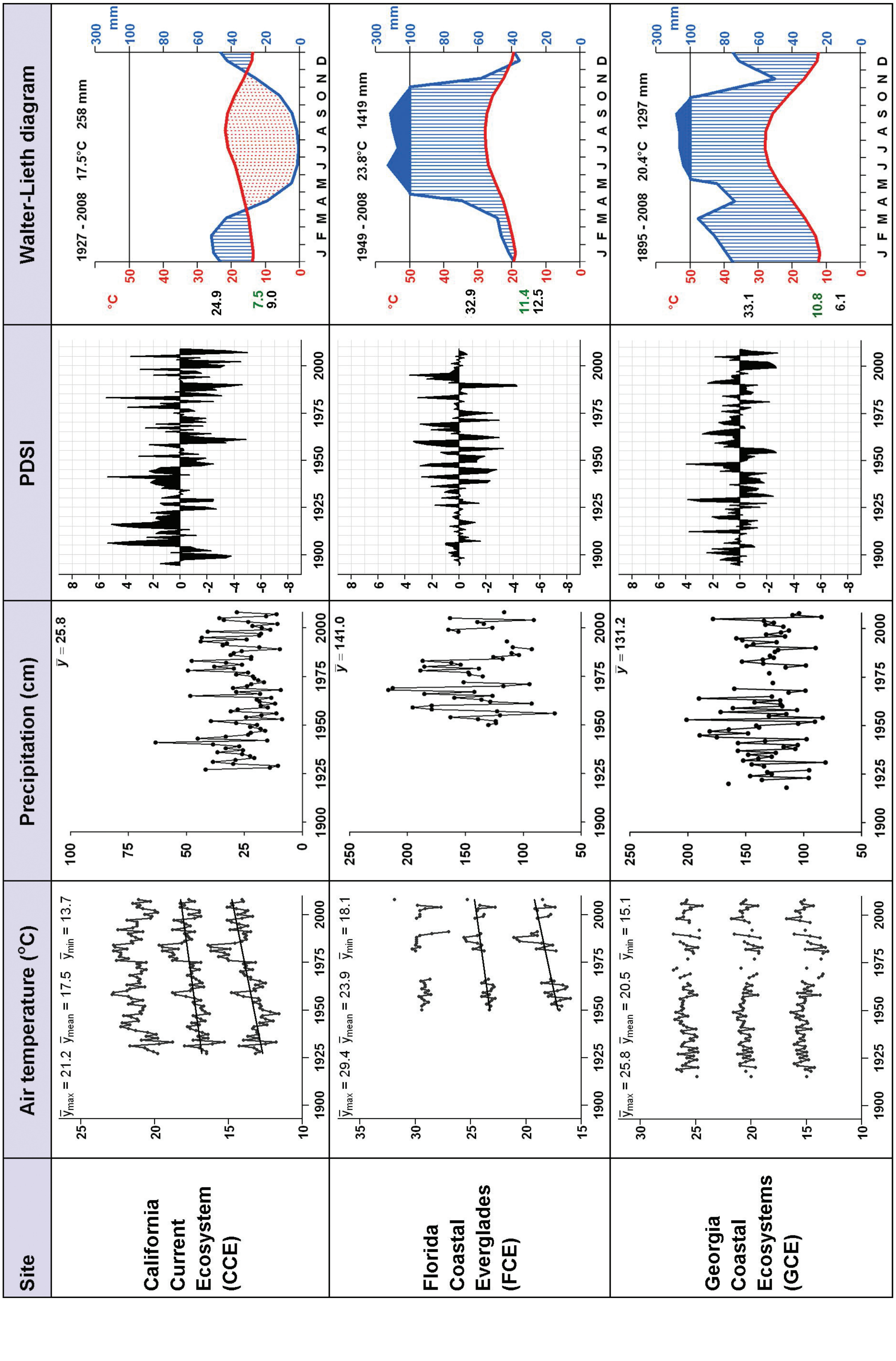
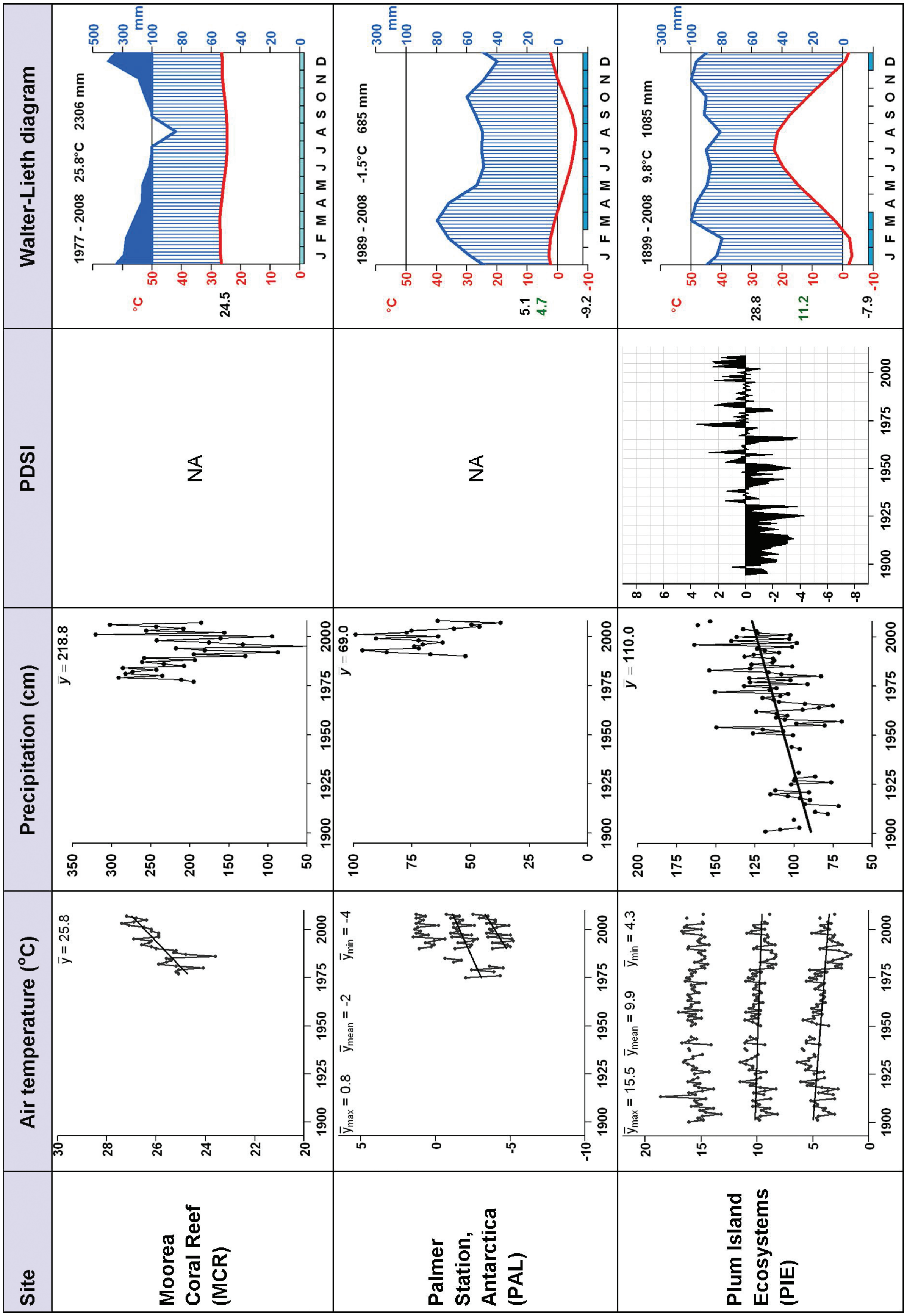


Figure 11-6 (coastal sites) continued next page.



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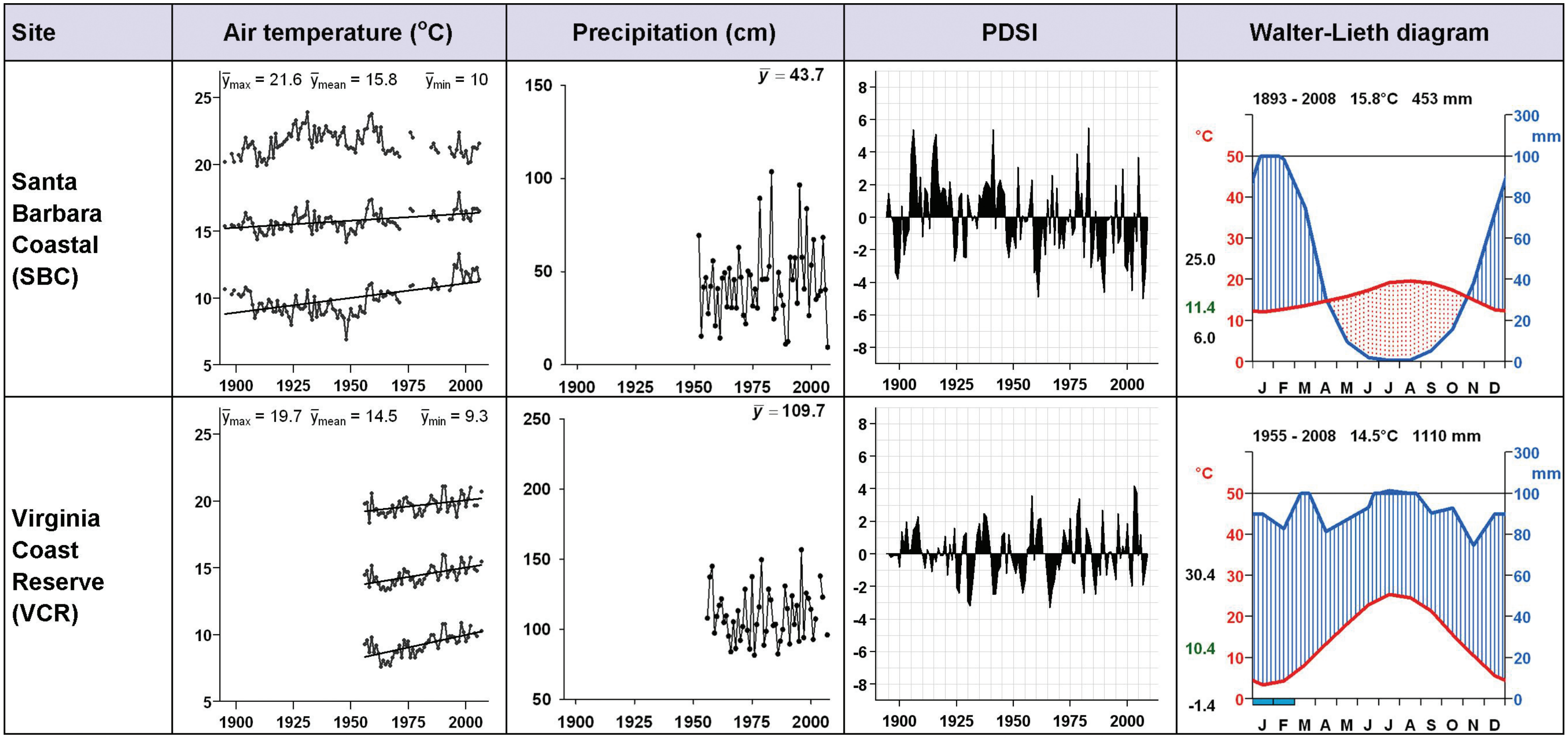
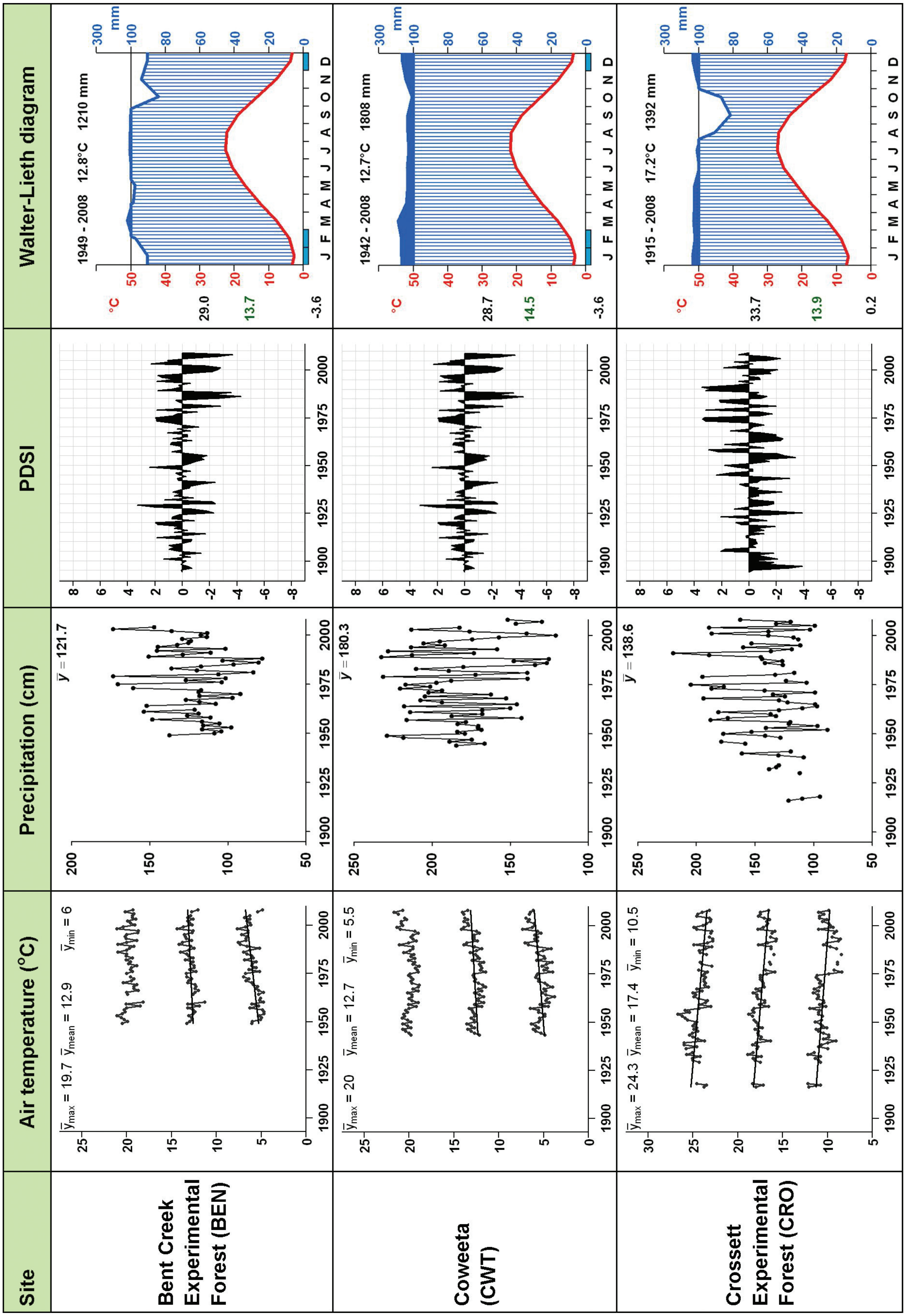


Figure 11-6. Trends for each coastal site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NA = not available, NS = non-significant) California Current Ecosystem (CCE): 0.026, 0.018, NS, NS; Florida Coastal Everglades (FCE): 0.037, 0.024, NS, NS; Georgia Coastal Ecosystems (GCE): NS, NS, NS, NS; Moorea Coral Reef (MCR): NA, 0.075, NA, NS; Palmer Station, Antarctica (PAL): 0.081, 0.059, NS, NS; Plum Island Ecosystems (PIE): -0.013, -0.006, NS, 0.360; Santa Barbara Coastal (SBC): 0.022, 0.010, NS, NS; and Virginia Coast Reserve (VCR): 0.037, 0.028, 0.019, NS. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. MCR climate data provided by Météo France en Polynésie Française. Synthesized data from http://www.ecotrends.info.



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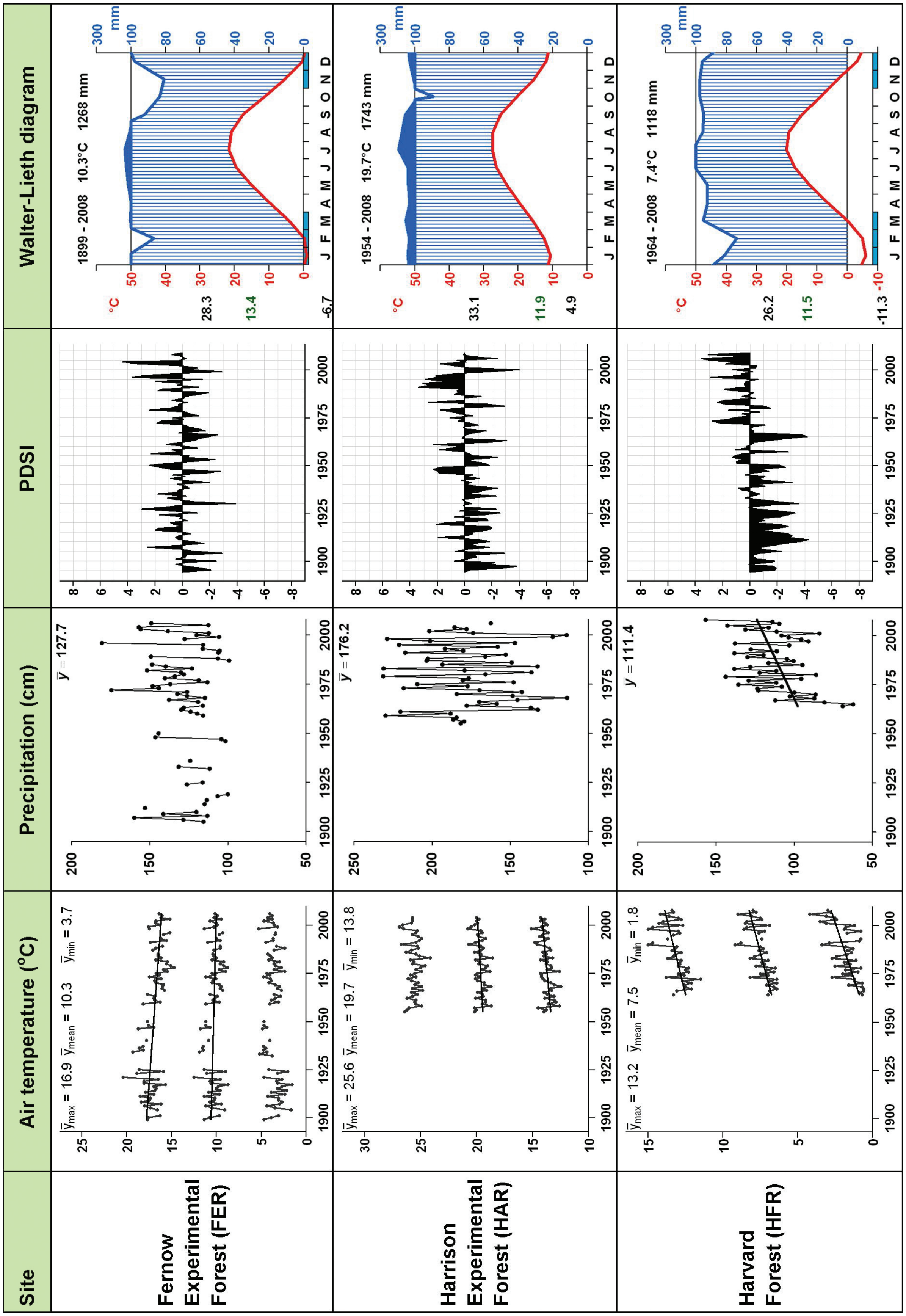

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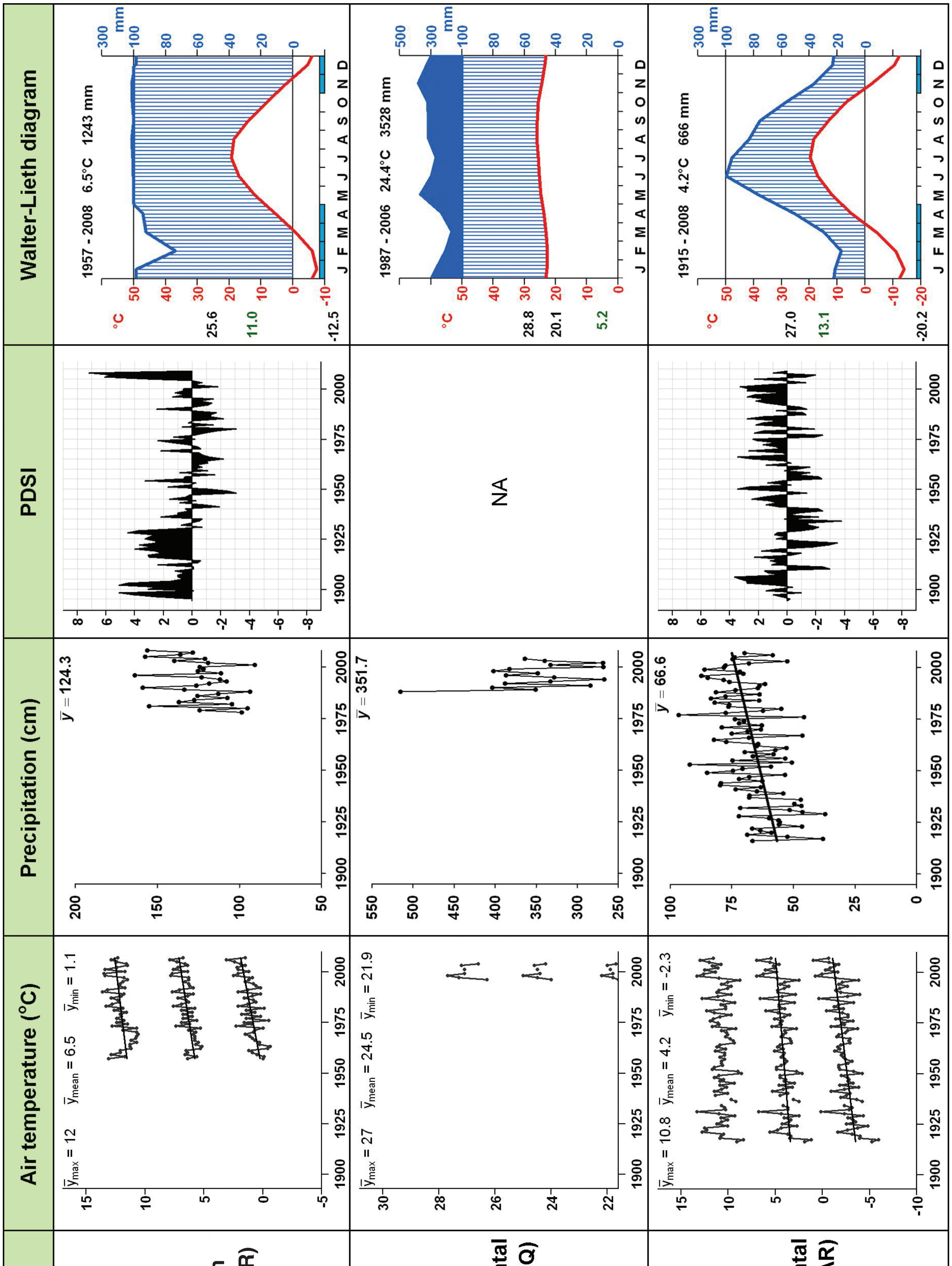

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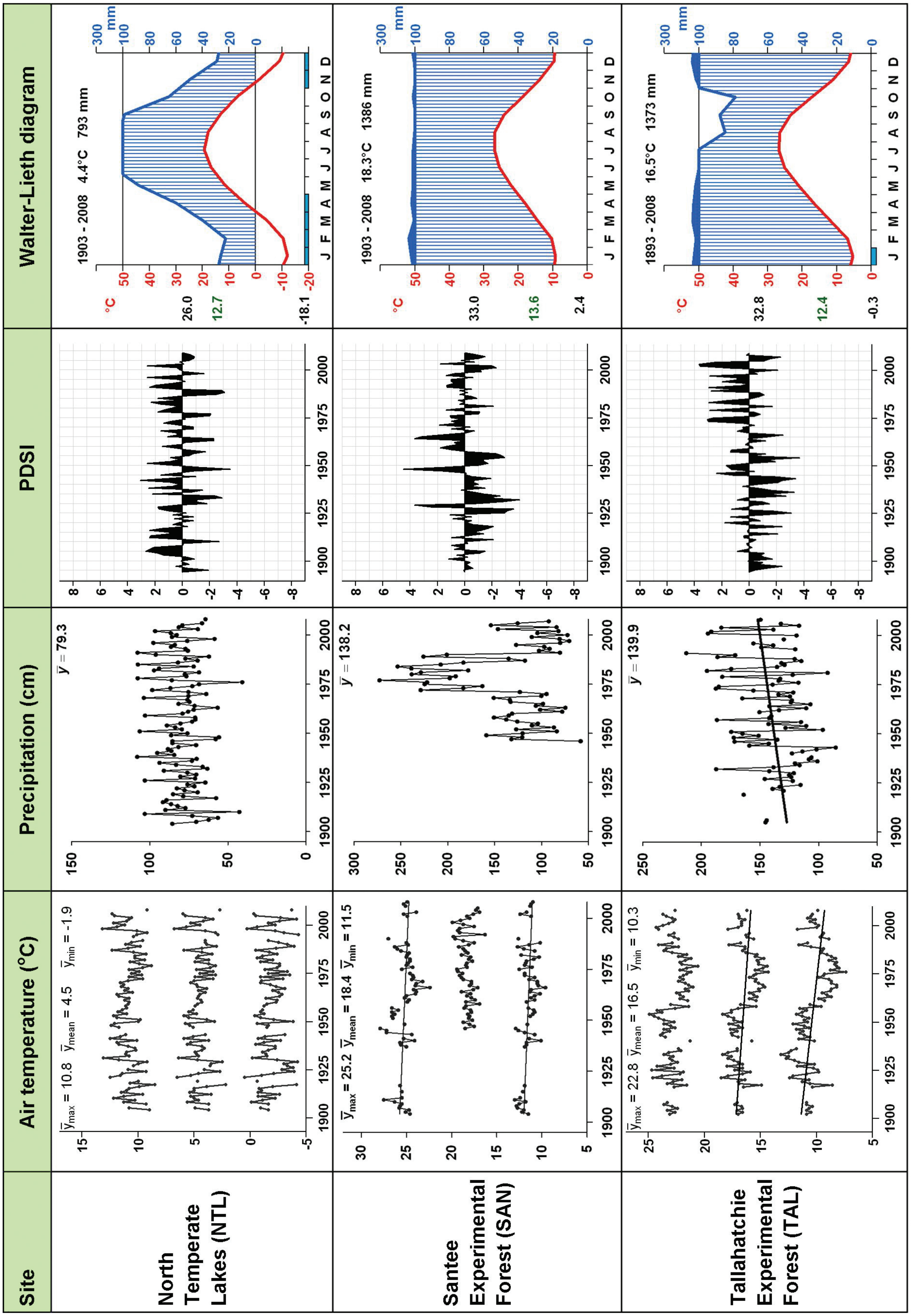

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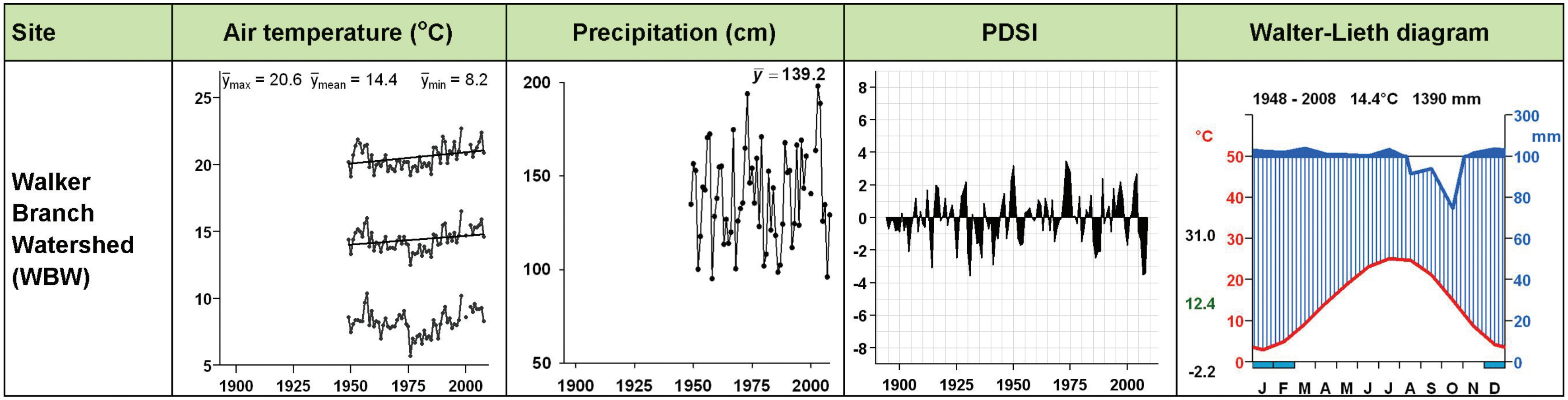

Figure 11-7. Trends for each eastern forest site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NS = non-significant) Bent Creek Experimental Forest (BEN): 0.025, 0.010, NS, NS; Crossett Experimental Forest (CRO): -0.017, -0.019, -0.021, NS; Coweeta (CWT): 0.017, 0.012, NS, NS; Fernow Experimental Forest (FER): NS, -0.006, -0.017, NS; Harrison Experimental Forest (HAR): 0.016, 0.010, NS, NS; Hubbard Brook Ecosystem Study (HBR): 0.033, 0.027, 0.020, NS; Harvard Forest (HFR): 0.043, 0.034, 0.032, 0.594; Luquillo Experimental Forest (LUQ): NS, NS, NS, NS; Marcell Experimental Forest (MAR): 0.027, 0.017, NS, 0.201; North Temperate Lakes (NTL): NS, NS, NS, NS; Santee Experimental Forest (SAN): -0.009, NS, -0.010, NS; Tallahatchie Experimental Forest (TAL): -0.020, -0.012, NS, 0.240; and Walker Branch Watershed (WBW): NS, 0.013, 0.017, NS. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

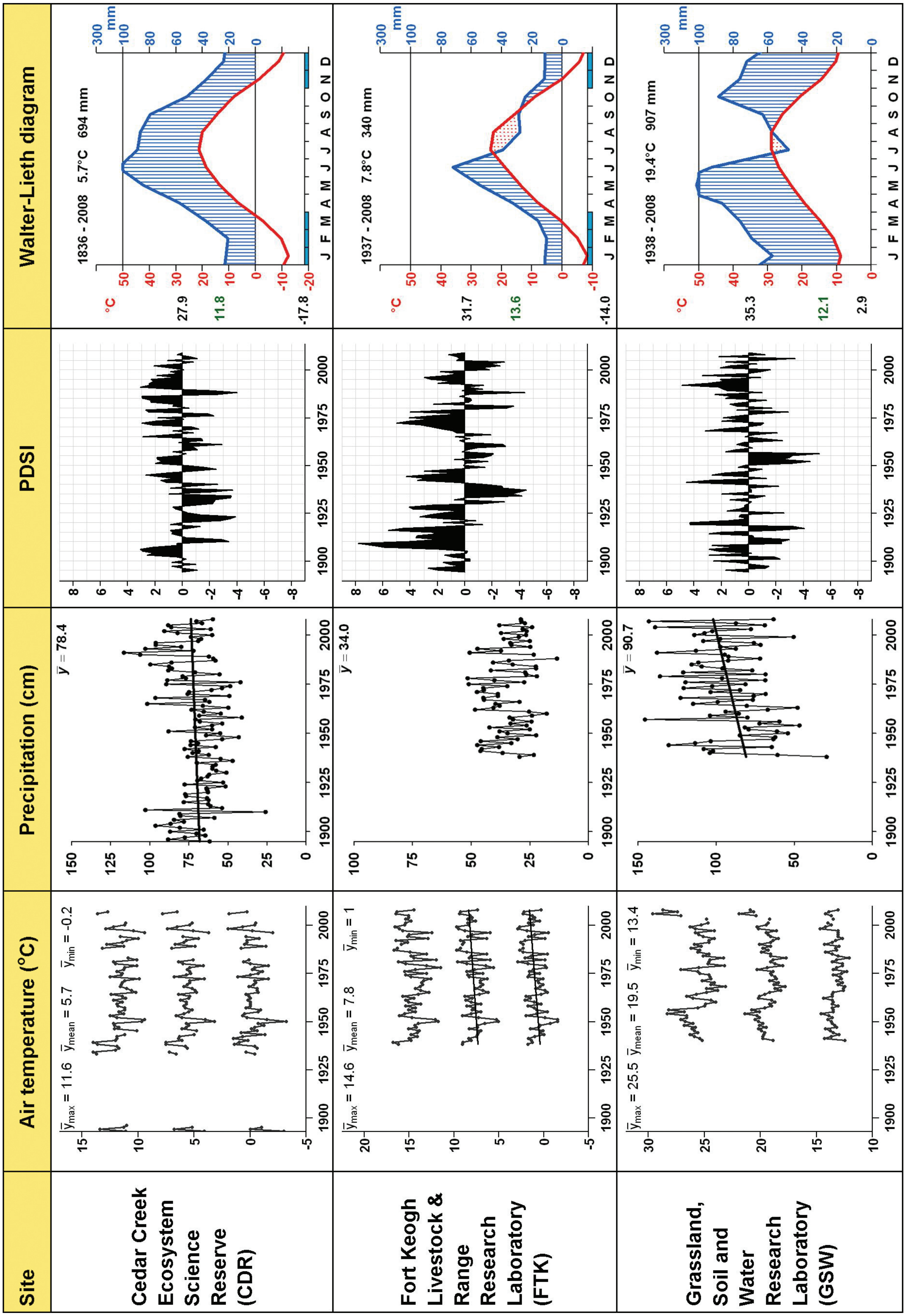

Figure 11-8 (grassland and savanna sites) continued next page.

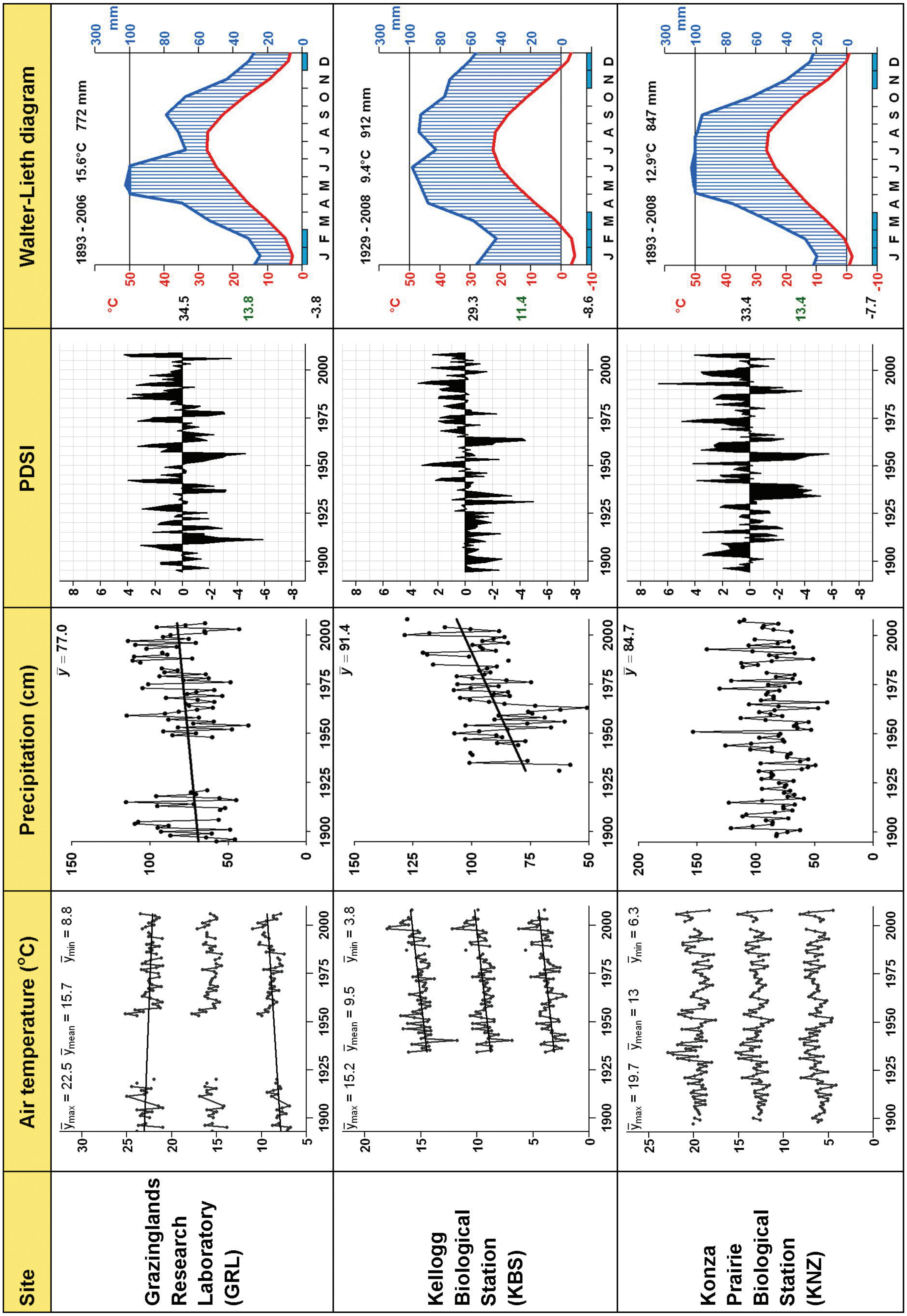

Figure 11-8 (grassland and savanna sites) continued next page.

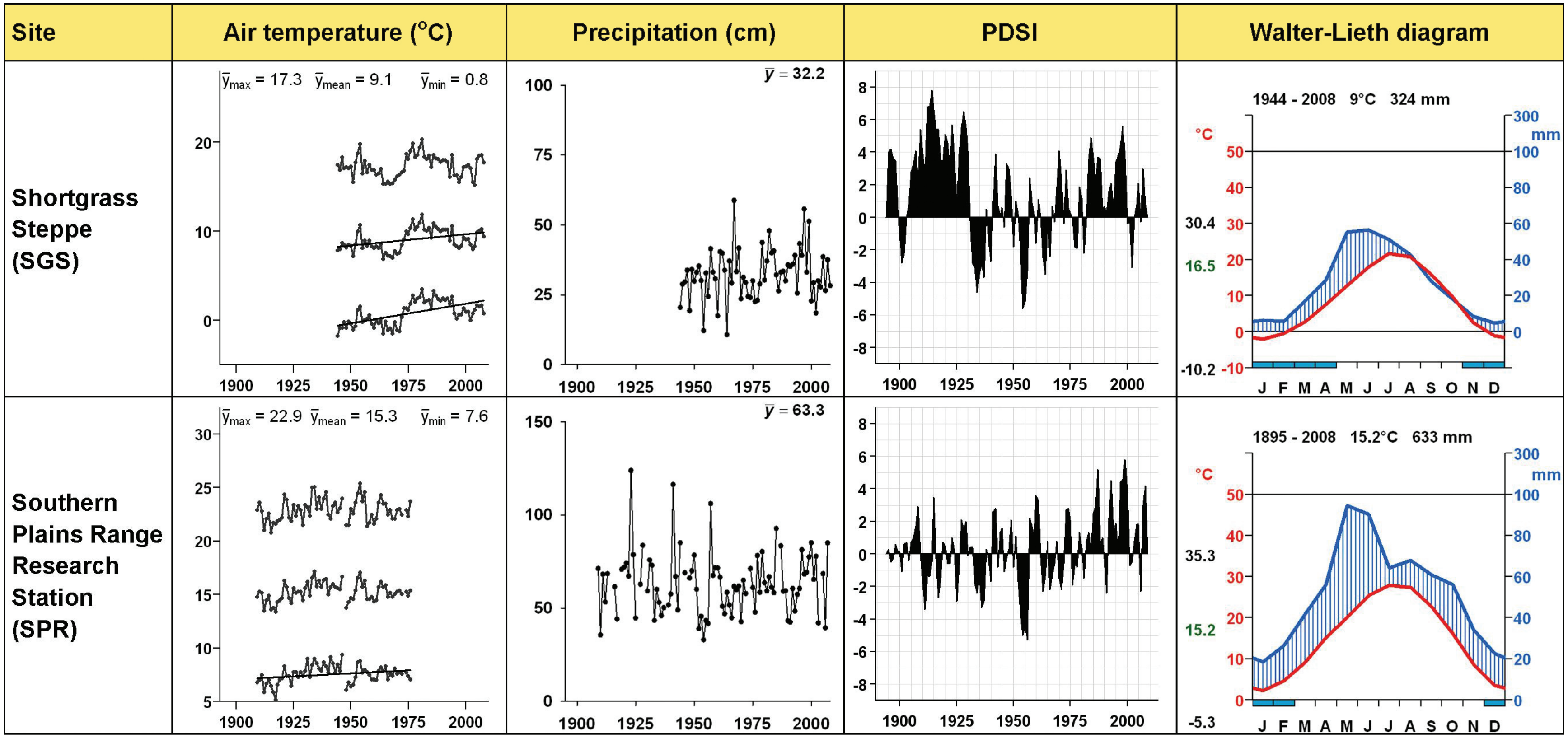

Figure 11-8. Trends for each temperate grassland and savanna site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NS = non-significant) Cedar Creek Ecosystem Science (CDR): NS, NS, NS, 0.049; Fort Keogh Livestock and Range (FTK): 0.017, 0.015, NS, NS; Grazinglands Research Laboratory (GRL): 0.019, NS, -0.013, 0.191; Grassland, Soil and Water Research Laboratory (GSW): NS, NS, NS, 0.300; Kellogg Biological Station (KBS): 0.019, 0.019, 0.019, 0.380; Konza Prairie Biological Station (KNZ): NS, NS, NS, NS; Shortgrass Steppe (SGS): 0.042, 0.024, NS, NS; and Southern Plains Range Research (SPR): 0.011, NS, NS, NS. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

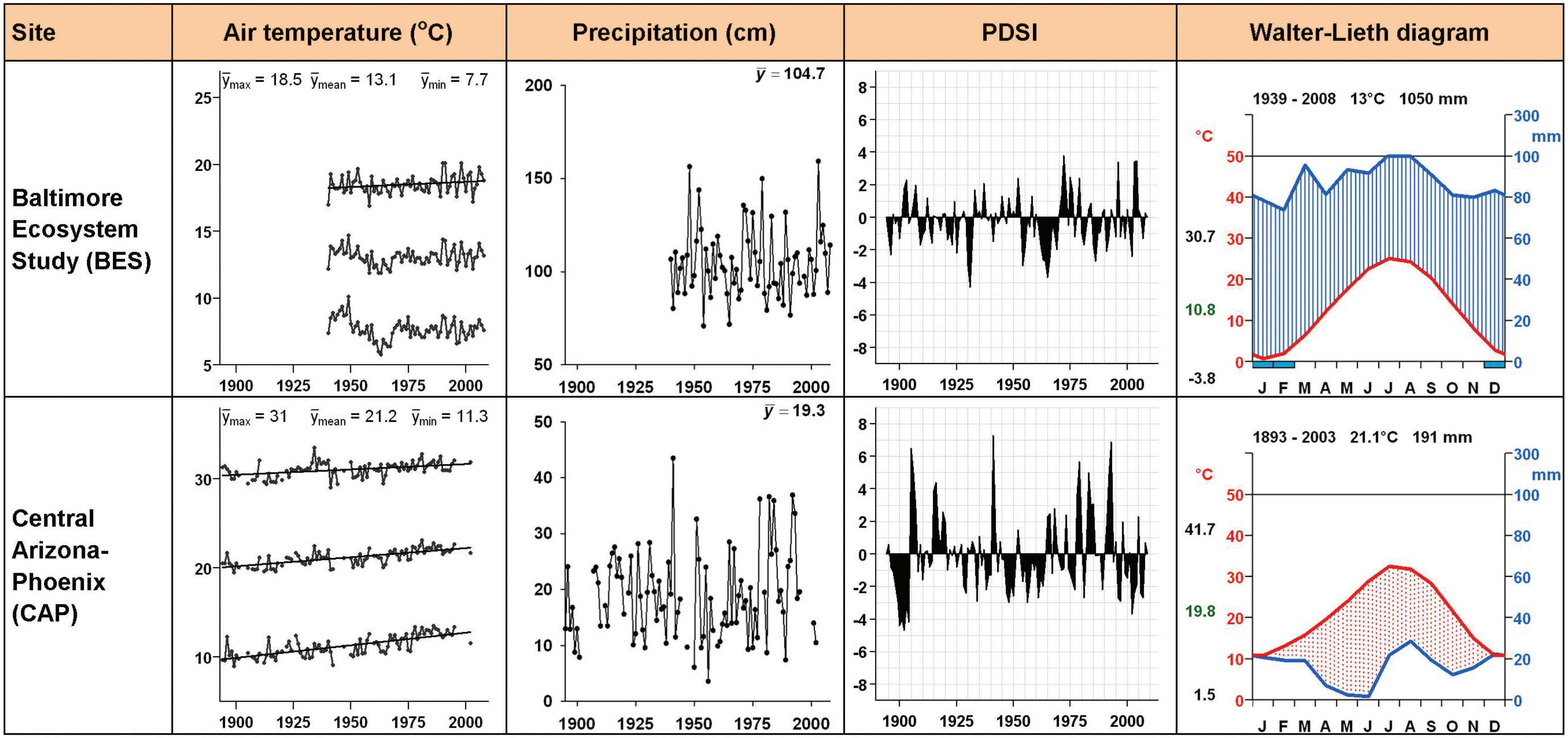

Figure 11-9. Trends for each urban site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NS = non-significant) Baltimore Ecosystem Study (BES): NS, NS, 0.008, NS and Central Arizona-Phoenix (CAP): 0.028, 0.020, 0.012, NS. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

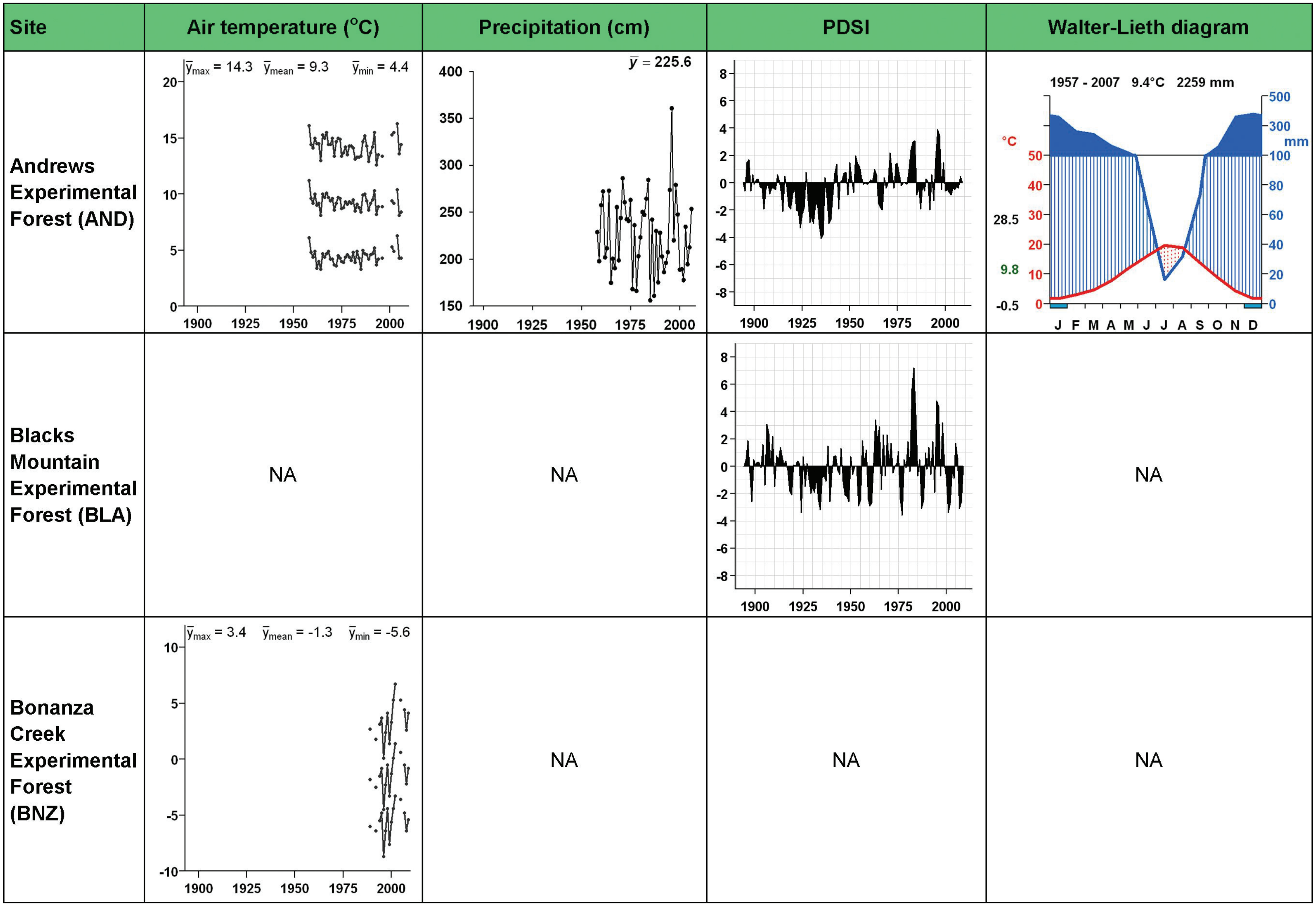

Figure 11-10 (western forest sites) continued next page.

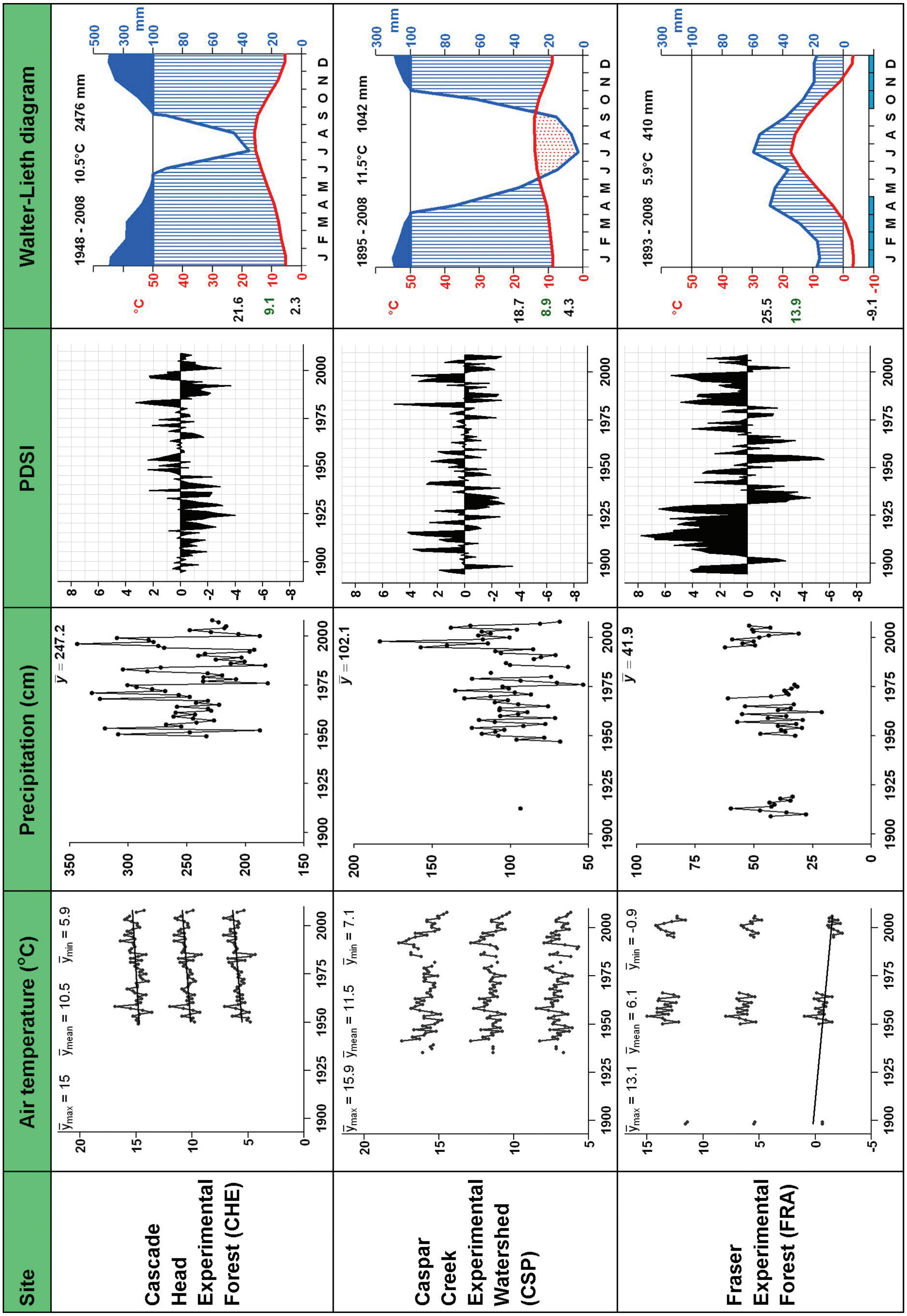

Figure 11-10 (western forest sites) continued next page.

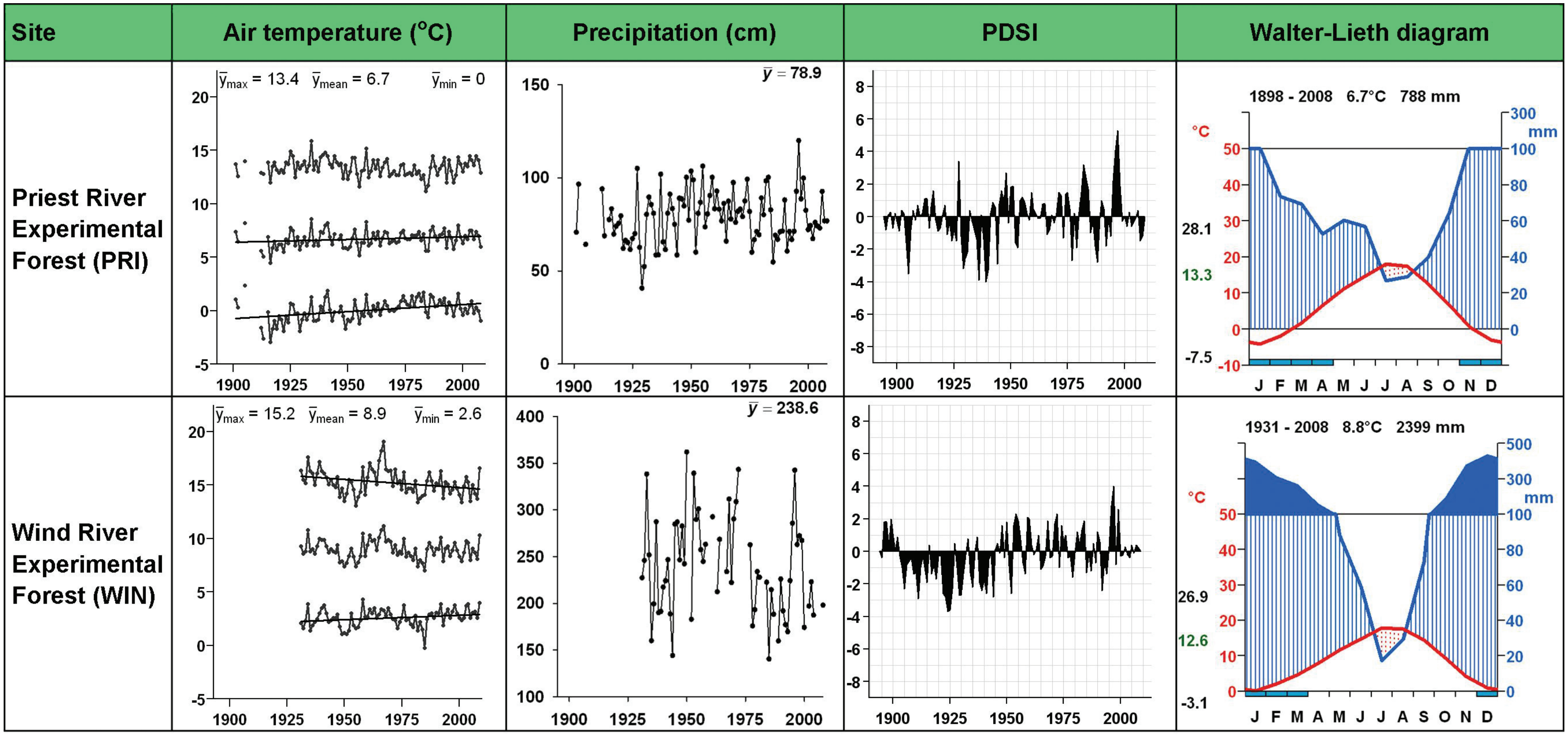

Figure 11-10. Trends for each western forest site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for minimum, mean, and maximum air temperature and precipitation, respectively, are (NA = not available, NS = non-significant) H.J. Andrews Experimental Forest (AND): NS, NS, NS, NS; Blacks Mountain Experimental Forest (BLA): NA, NA, NA, NA; Bonanza Creek Experimental Forest (BNZ): NS, NS, NS, NA; Cascade Head Experimental Forest (CHE): 0.014, 0.012, 0.010, NS; Caspar Creek Experimental Watershed (CSP): NS, NS, NS, NS; Fraser Experimental Forest (FRA): -0.033, NS, NS, NS; Priest River Experimental Forest (PRI): 0.014, 0.006, NS, NS; and Wind River Experimental Forest (WIN): 0.009, NS, -0.015, NS. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

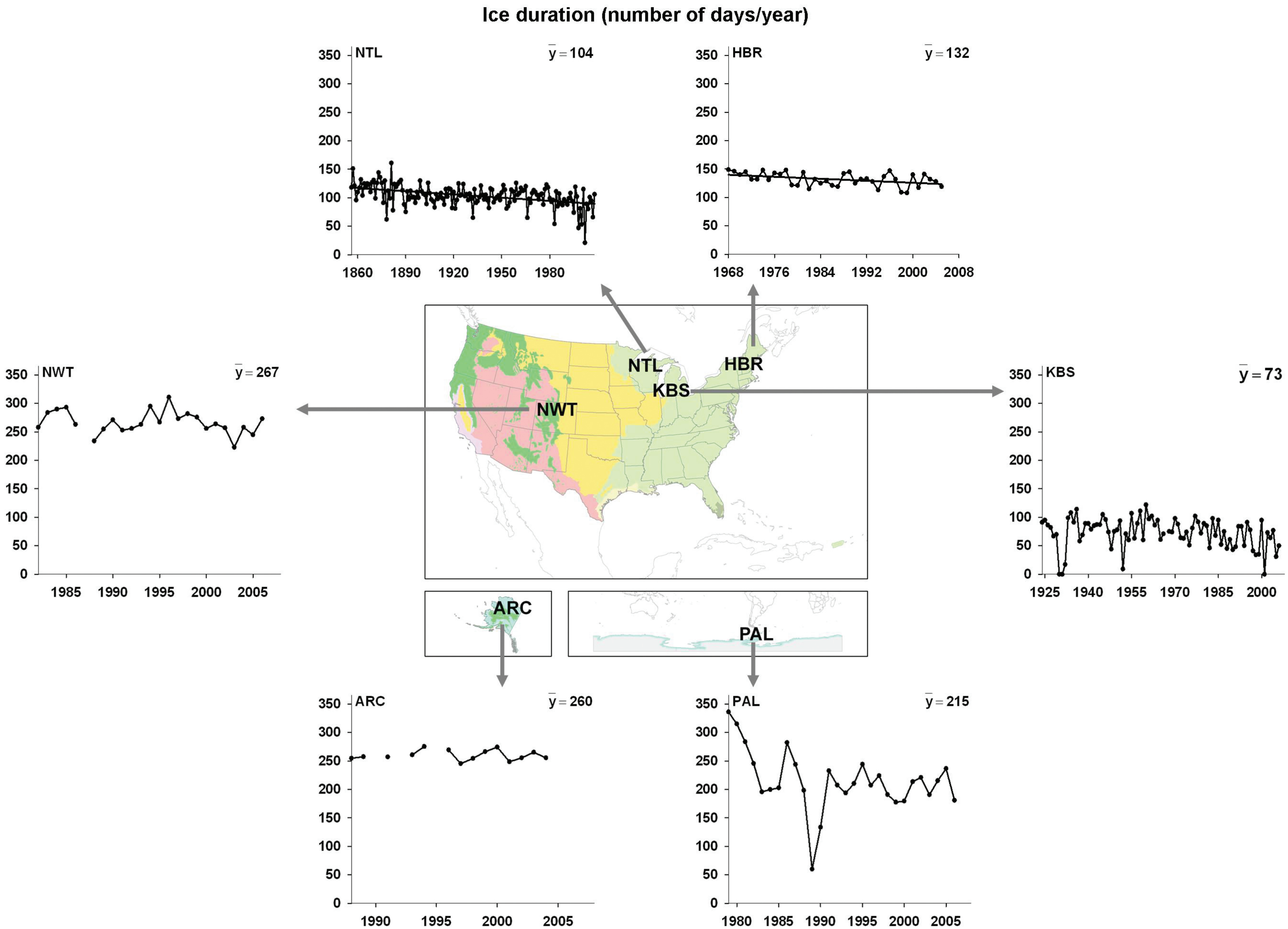

Figure 11-11. Ice duration (number of days per year) through time and the mean number of days per year for six sites with data. Length of the time series differs among sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Hubbard Brooks Ecosystem Study (HBR) (-0.447) and North Temperate Lakes (NTL) (-0.187). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

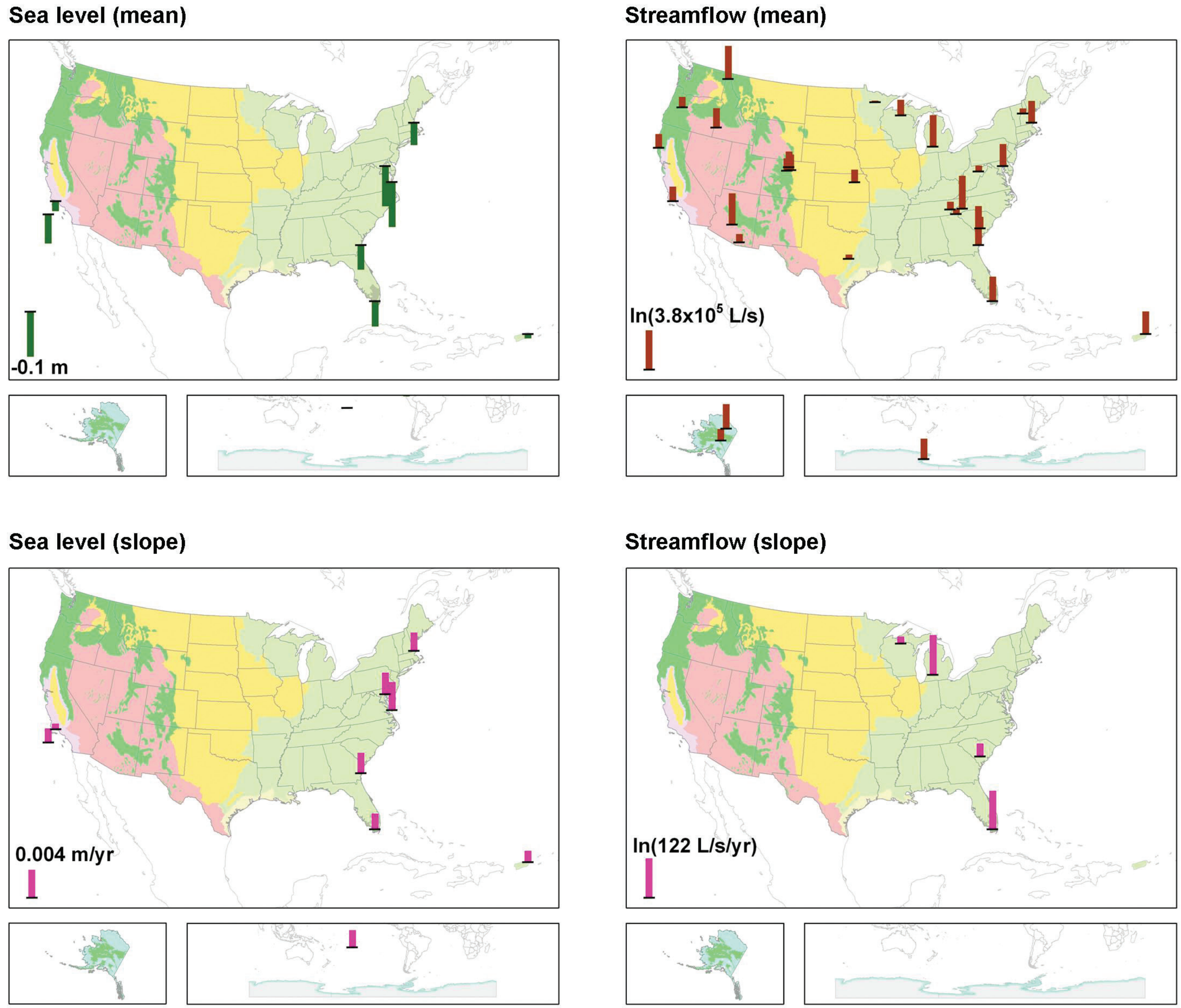

Figure 11-12. Continental patterns in annual mean sea level (m) and streamflow (L/s). Annual mean sea level is defined as the annual arithmetic mean of hourly heights relative to the National Tidal Datum Epoch (the most recent mean sea level datum established by the Center for Operational Oceanographic Products and Services (CO-OPS), currently the mean sea level 1983-2001). (Top panels) long-term averages: positive values are red and negative values are green. (Bottom panels) slopes of significant regression lines ($p < 0.05$): positive values are pink and negative values are blue. For streamflow, the bar height is the ln-transformed value [ln(1+mean), ln(slope)]. Original data from Internet home pages (see table 1-1) and http://www.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

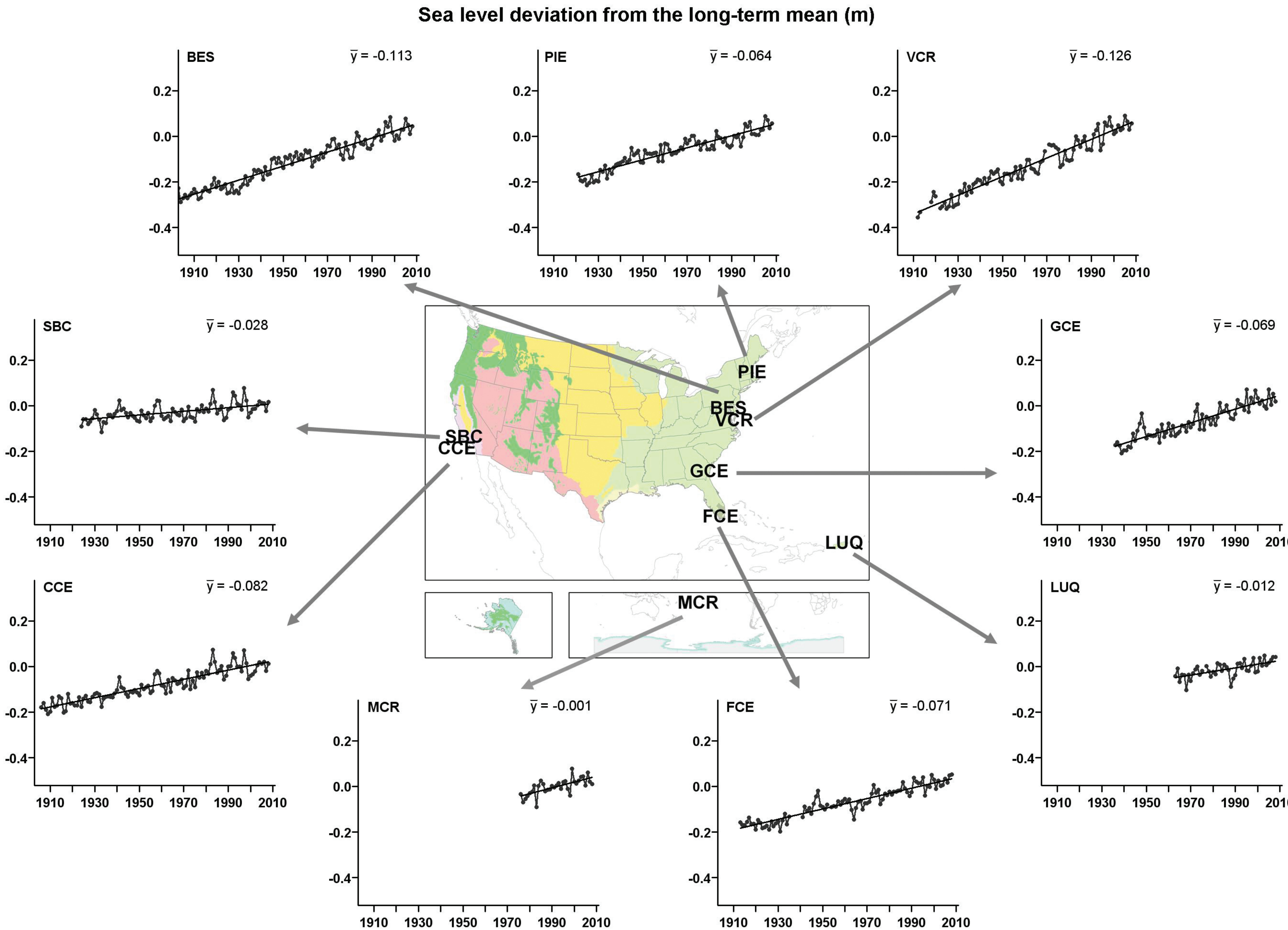

Figure 11-13. Annual mean sea level (m) through time for nine sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Santa Barbara Coastal (SBC): 0.001; California Current Ecosystem (CCE), Florida Coastal Everglades (FCE), and Luquillo Experimental Forest (LUQ): 0.002; Georgia Coastal Ecosystems (GCE), Moorea Coral Reef (MCR), Plum Island Ecosystems (PIE), and Baltimore Ecosystem Study (BES): 0.003; and Virginia Coast Reserve (VCR): 0.004. Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

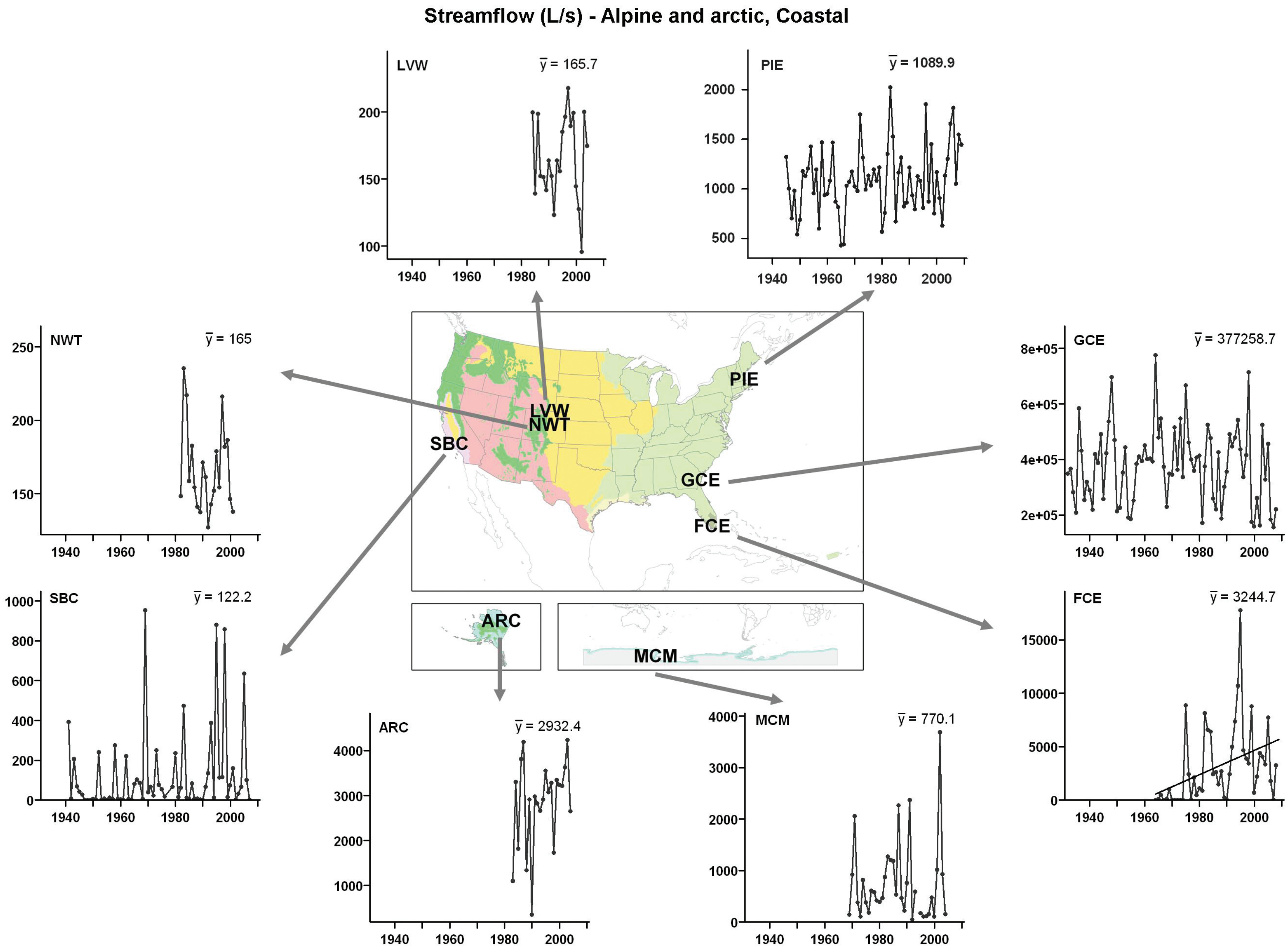

Figure 11-14. Streamflow (L/s) through time for eight alpine and arctic sites and coastal sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slope is Florida Coastal Everglades (FCE) (110.6). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

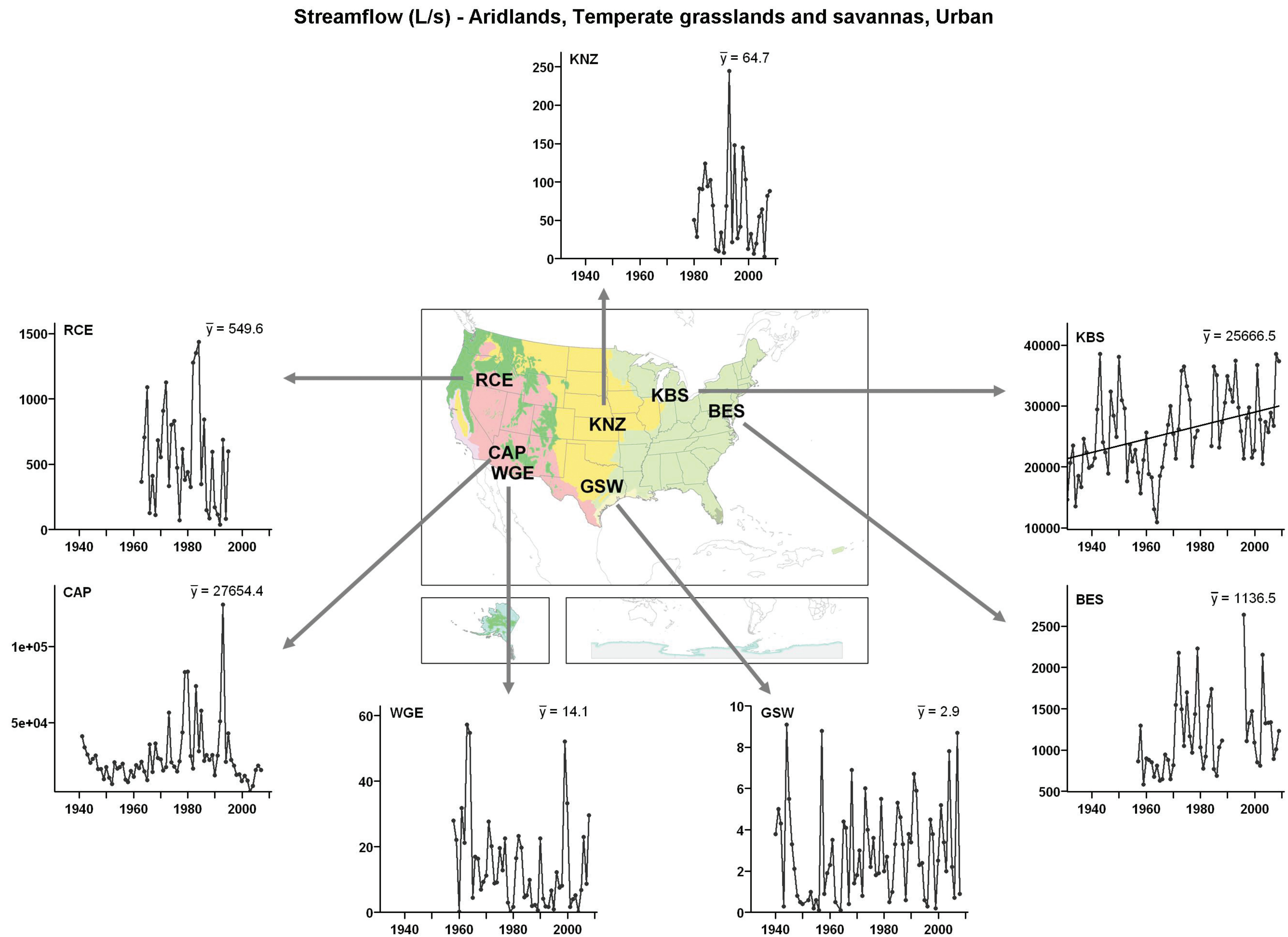

Figure 11-15. Streamflow (L/s) through time for seven aridland, temperate grassland and savanna, and urban sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slope is Kellogg Biological Station (KBS) (122.1). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

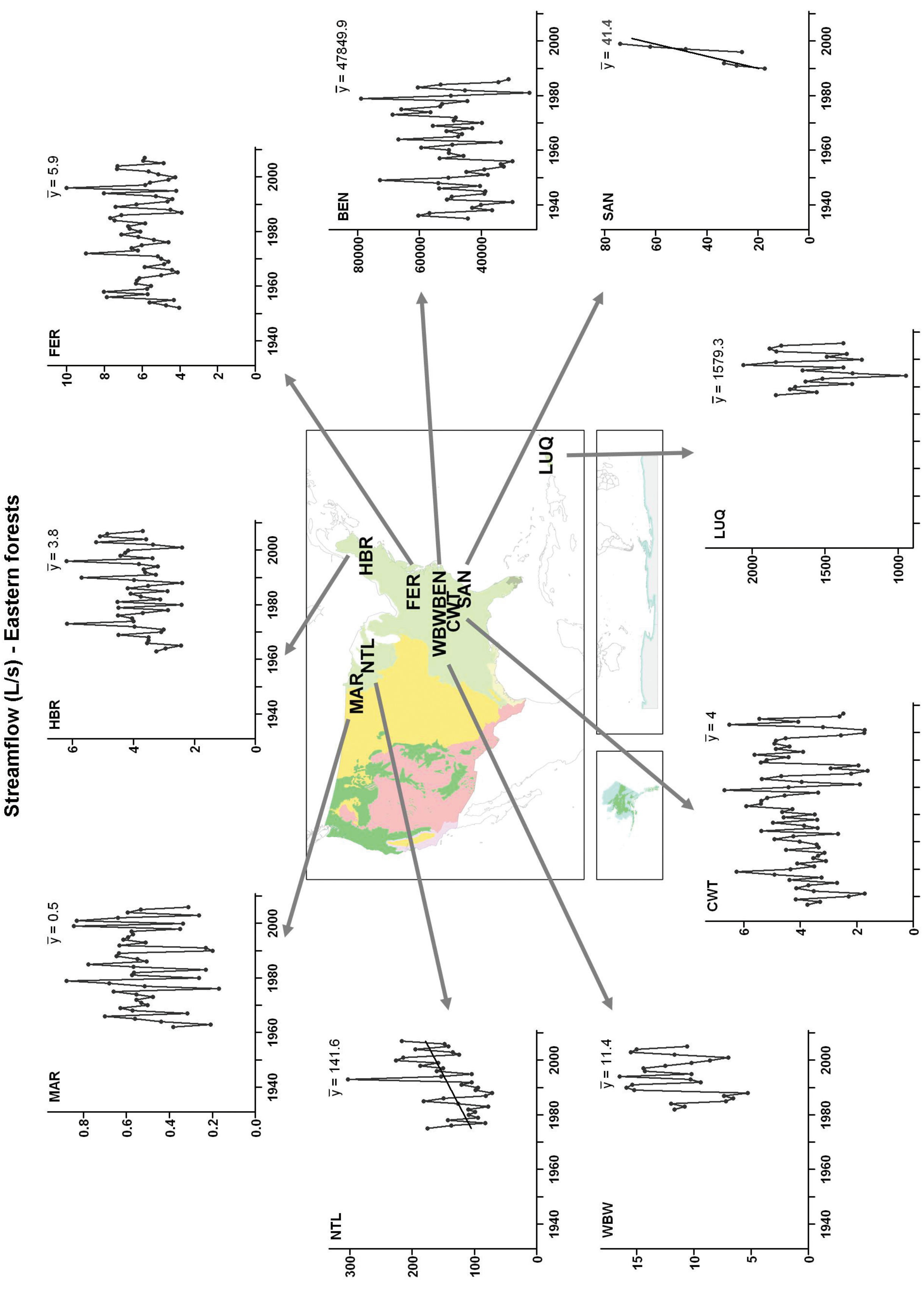

Figure 11-16. Streamflow (L/s) through time for nine eastern forest sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are North Temperate Lakes (NTL) (2.3) and Santee Experimental Forest (SAN) (4.9). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

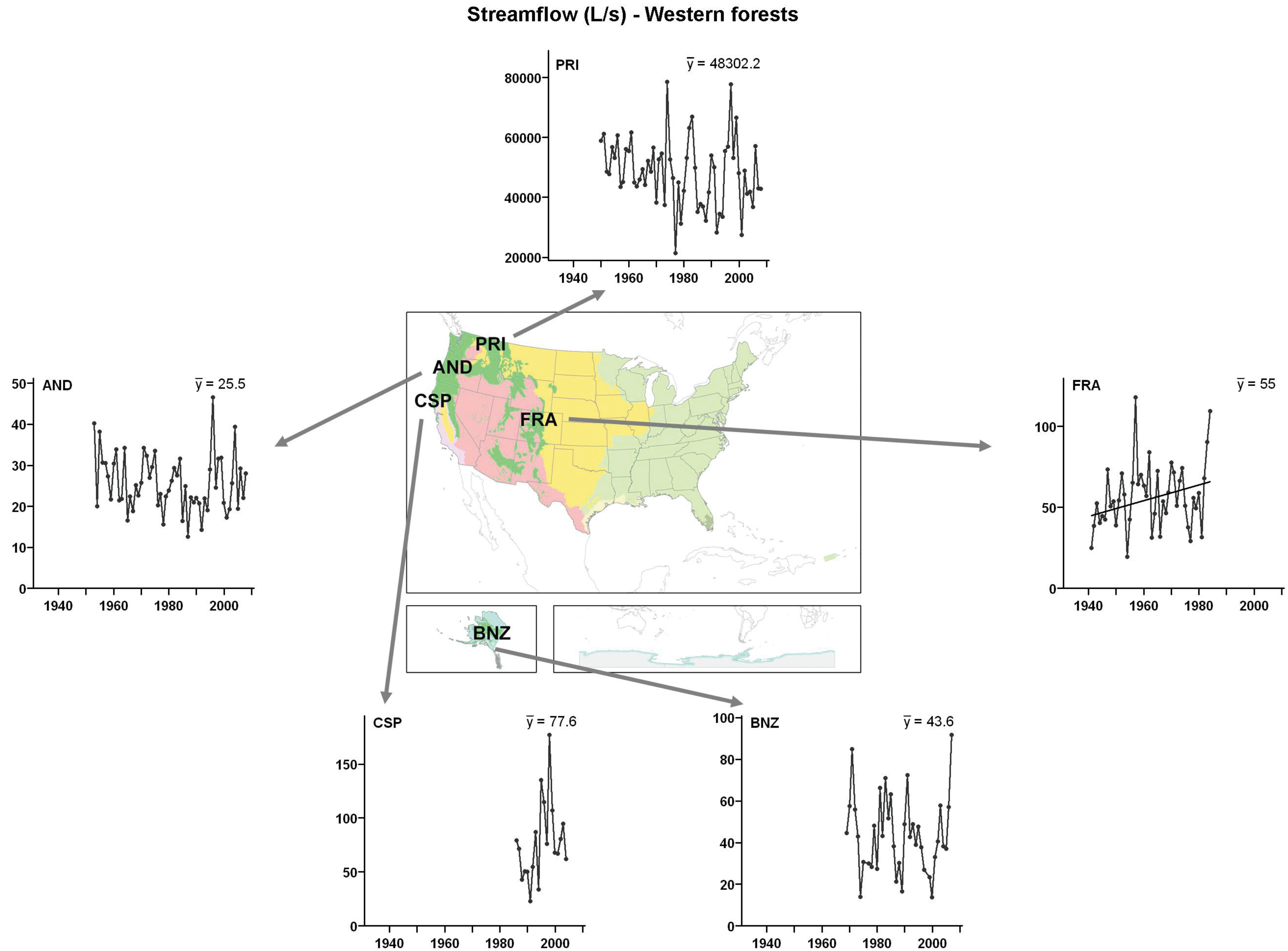

Figure 11-17. Streamflow (L/s) through time for five western forest sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

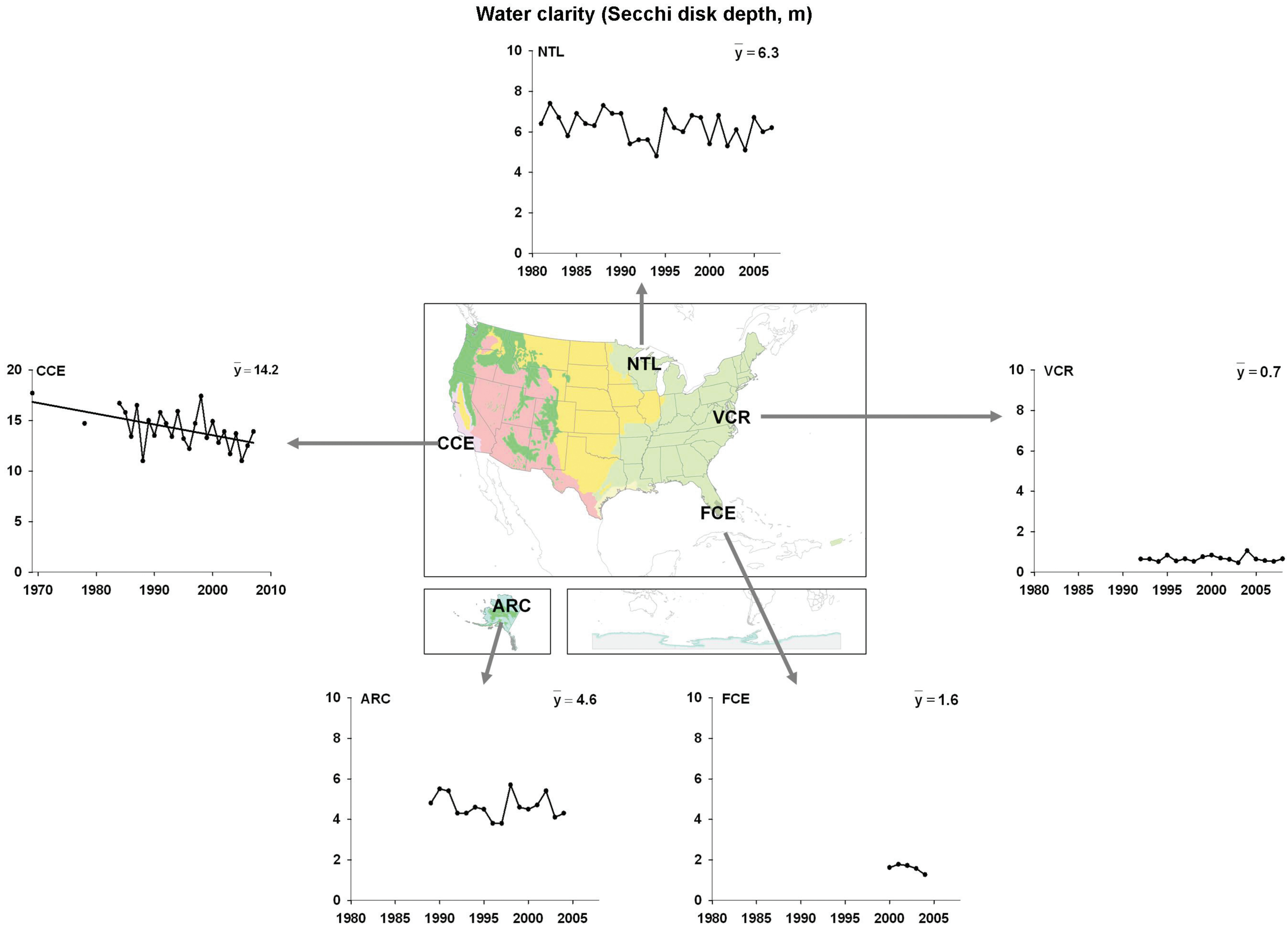

Figure 11-18. Water clarity (as Secchi disk depth, m) through time for five sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slope is California Current Ecosystem (CCE) (-0.1). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

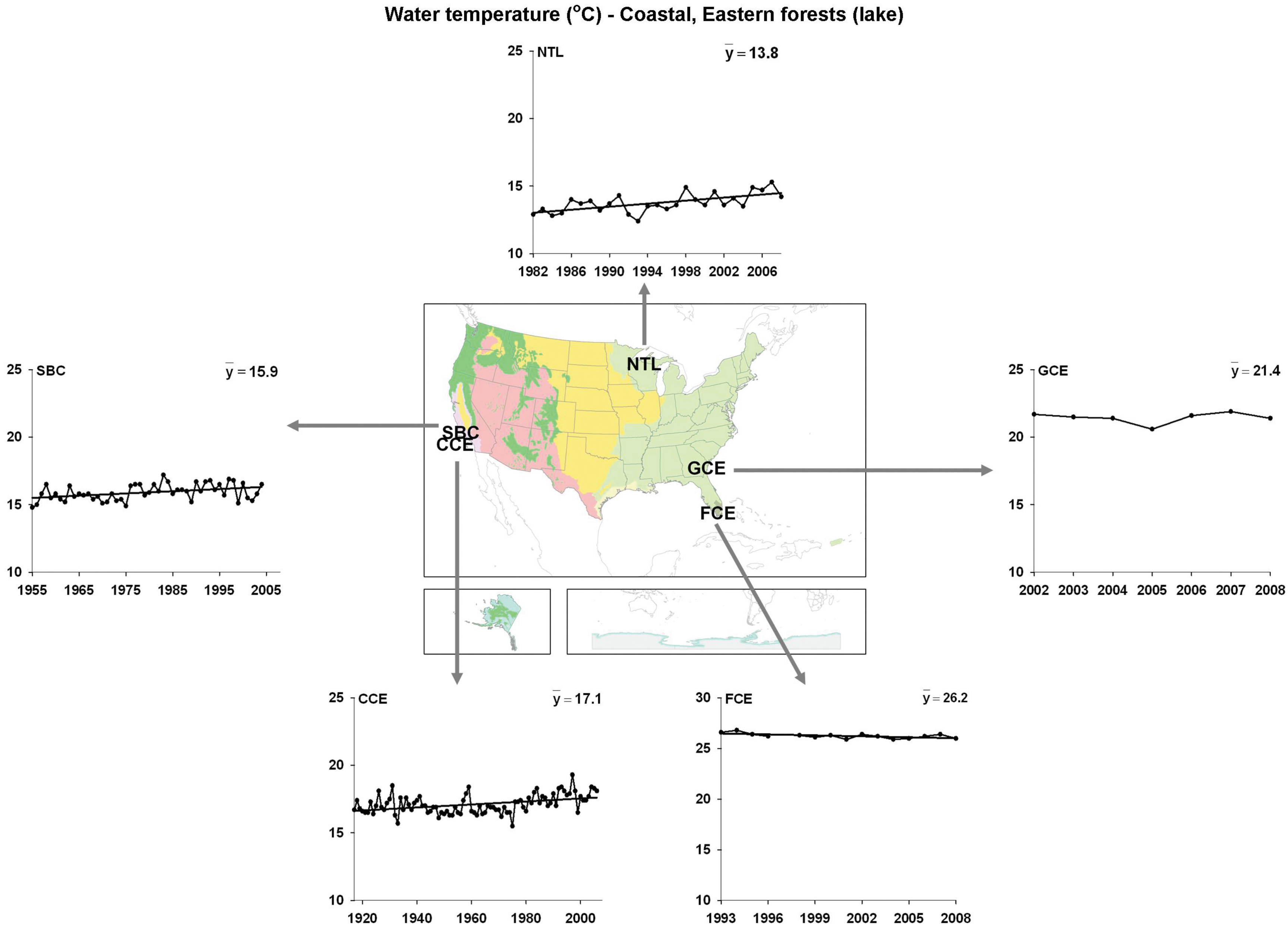

Figure 11-19. Water temperature (°C) through time for five coastal sites and one lake in an eastern forest site. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are: California Current Ecosystem (CCE) (0.01), Florida Coastal Everglades (FCE) (-0.03), Santa Barbara Coastal (SBC) (0.02), and North Temperate Lakes (NTL) (0.06). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

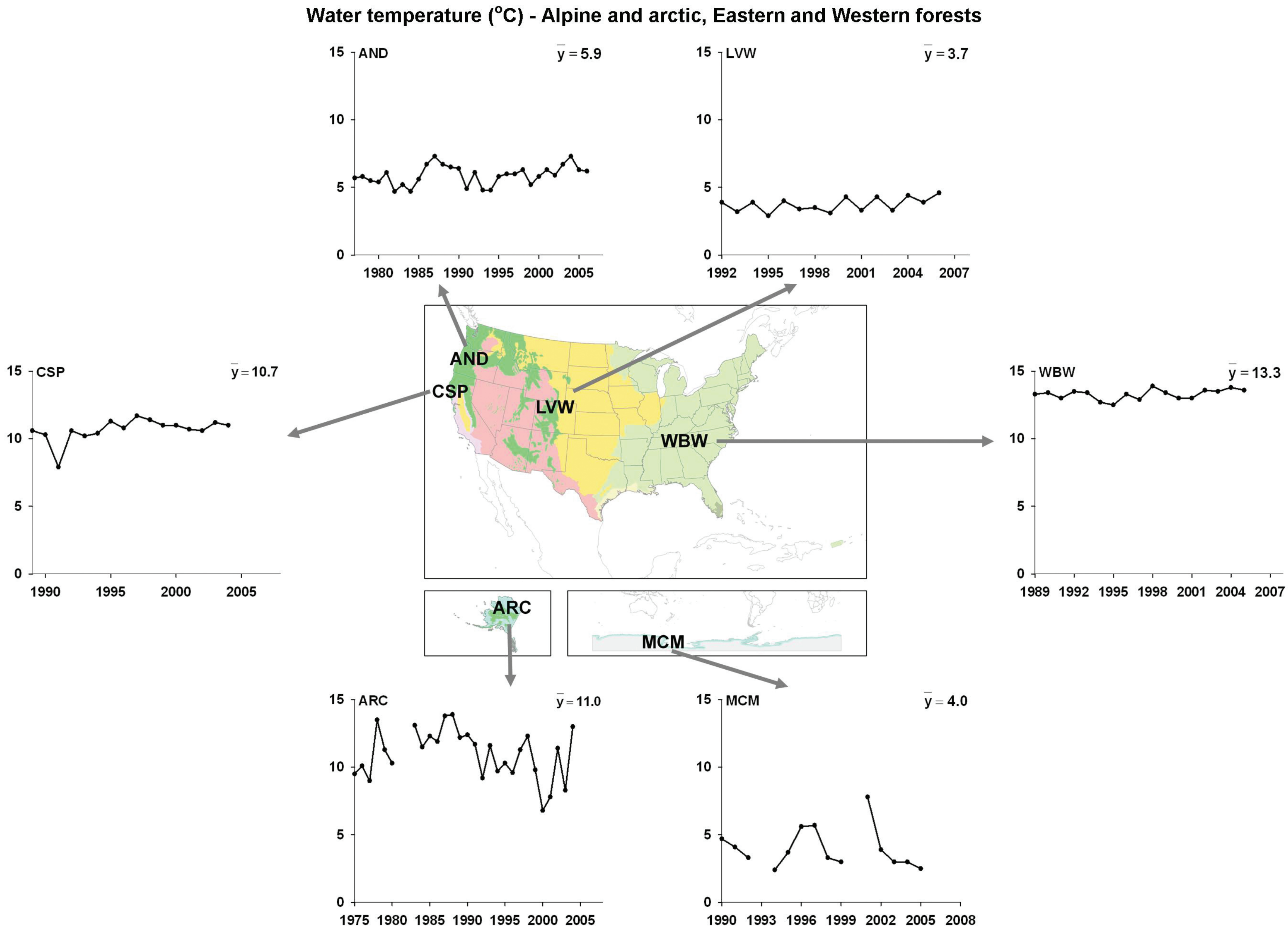

Figure 11-20. Water temperature (°C) through time for streams in six alpine and arctic sites and eastern and western forest sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

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Chapter 12

Long-Term Trends in Precipitation and Surface Water Chemistry

In this chapter, we first describe common methods to measure precipitation and water chemistry, as well as our rationale for the selection of variables in the book. We then show graphs of long-term data summarized across sites and by site for four major elements (nitrogen and sulfur, in precipitation as inputs and surface water as export, and calcium and choride). Examples of research questions that can be addressed using these data can be found in chapter 6. Data for additional elements are available on the EcoTrends website (http://www.ecotrends.info).

Methods of Measurements and Selection of Variables

One of the challenges associated with conducting cross-site analyses of long-term biogeochemistry data is that sites in different biomes focus on different research questions and use different approaches to address these questions. A second problem is that biogeochemical research has typically focused on measurements of the inputs to and losses from ecosystems rather than pool sizes and transfers among pools. Inputs often provide information on important drivers to ecosystem function. Losses provide an indication of the response of ecosystems to changes in environmental drivers. Losses or export of nitrogen in surface water depend on the ability of vegetation to retain nitrogen. This retention is affected by soil, vegetation, hydrologic properties, and climate. Nitrate is much more mobile than ammonium (which is often very low in streams) and is recognized as an indicator of watershed's nitrogen status. The ability of watersheds to retain nitrogen is important in preventing its movement downstream to waters that are sensitive to nitrogen-induced eutrophication (examples include the Chesapeake Bay and the Gulf of Mexico).

Although study of internal element pools and transfers among pools is essential to understanding ecosystem function, obtaining the data is often difficult and expensive and generally is not part of routine monitoring. Thus, no long-term data on soil chemistry are available for cross-site comparisons. However, cross-site comparisons from short-duration nitrogen fertilization studies are discussed in chapter 6.

In this chapter, we focus on measurements made using common methods for a relatively large number of sites (up to 34). As a result, we focus on (1) wet deposition and precipitation chemistry through data available either in the National Atmospheric Deposition Program (NADP; http://nadp.sws.uiuc.edu/) or from a site and (2) on surface water chemistry collected by each site.

Two measures of wet deposition are commonly obtained from precipitation (rain, snow) collected at a site: (1) concentration, expressed as milligrams per liter, is measured on a subsample of the precipitation collected and averaged based on the total volume collected (the volume-weighted concentration), and (2) total amount collected in a precipitation sample is converted to an areal basis (deposition expressed as kg/ha per year). In both cases, samples are collected frequently (daily or weekly, for example) and converted to a mean value for the entire year. In most cases, data were obtained for nitrate, ammonium, chloride, hydrogen (acidity as pH), and base cations (calcium, magnesium, potassium, and sodium). Nitrate is an important nutrient for the biota, although it can be toxic at high levels. The dominant source of nitrate emissions to the atmosphere is combustion of fossil fuels from transportation sources and electric utilities. Ammonium, which can be toxic at high levels, is an important byproduct of animal metabolism and fertilization. Sources and atmospheric deposition of ammonia (figure 12-9) typically vary more locally than those of nitrate, which tends to show strong regional patterns (figure 12-1). Additional elements and finer resolution data are available on the EcoTrends website (http://www.ecotrends.info). Concentrations of all of these solutes are changing in precipitation in response to changes in emissions of air pollutants, and these changes have implications for water quality and ecosystems. Mean surface water export data on an annual basis (mg/L) for nitrate, ammonium, sulfate, chloride, and calcium are shown here.

Graphs Showing Long-Term Trends

The remainder of this chapter is devoted to graphs showing trends in precipitation and surface water chemistry, displayed in two ways, to provide a sense of change across a range of spatial scales (continent, site) for each variable. First, we provide a summary of trends at the continental scale using maps that show either the mean across years or the slope of the regression line (if significant) across time for each variable. Slopes are shown using either pink (positive) or blue (negative) bars; the height of the bar is the magnitude of the slope.

Following the continental-scale maps, we show data through time using three panels for each site and each variable: (1) concentration in precipitation (mg/L), (2) deposition in precipitation (kg/ha/y), and (3) concentration in surface water (mg/L). These panels allow comparisons between atmospheric deposition (inputs) and the amount of nitrogen lost from surface water each year. A line indicates a significant positive or negative trend through time ($p < 0.05$) based on simple linear regression, uncorrected for autocorrelation. The site graphs are organized by ecosystem type to allow comparisons of sites in the same ecosystem. For surface water, we show each site graph on a continental map with similar sites to allow direct comparisons among sites. Long-term means and regression coefficients can be found in Appendices 5-14.

Summary

Trends in nitrogen compounds vary through time within a site and spatially among sites because of the multiple forms of nitrogen in ecosystems with different sources and dynamics. Nitrates in precipitation are either decreasing (in the East) or not changing at most sites. Notable exceptions are sites in the Rocky Mountains (NWT) and sites with rapidly increasing urban populations near a research site (FCE). Patterns in nitrate export from streams and lakes are more variable in that some sites are increasing, some are decreasing, and many remain unchanged. Ammonium deposition either has not changed or is increasing over the past 20 plus years. Given that nitrate is not changing or is declining for many sites outside of the Rocky Mountains, ammonium is increasing in importance as a component of atmospheric deposition nationally. Nitrate and sulfate deposition are decreasing in many eastern sites, consistent with efforts to control emissions of acid-causing nitrogen and sulfur from power plants in that part of the country. Declines in nitrate deposition have not been as marked as declines in sulfate.

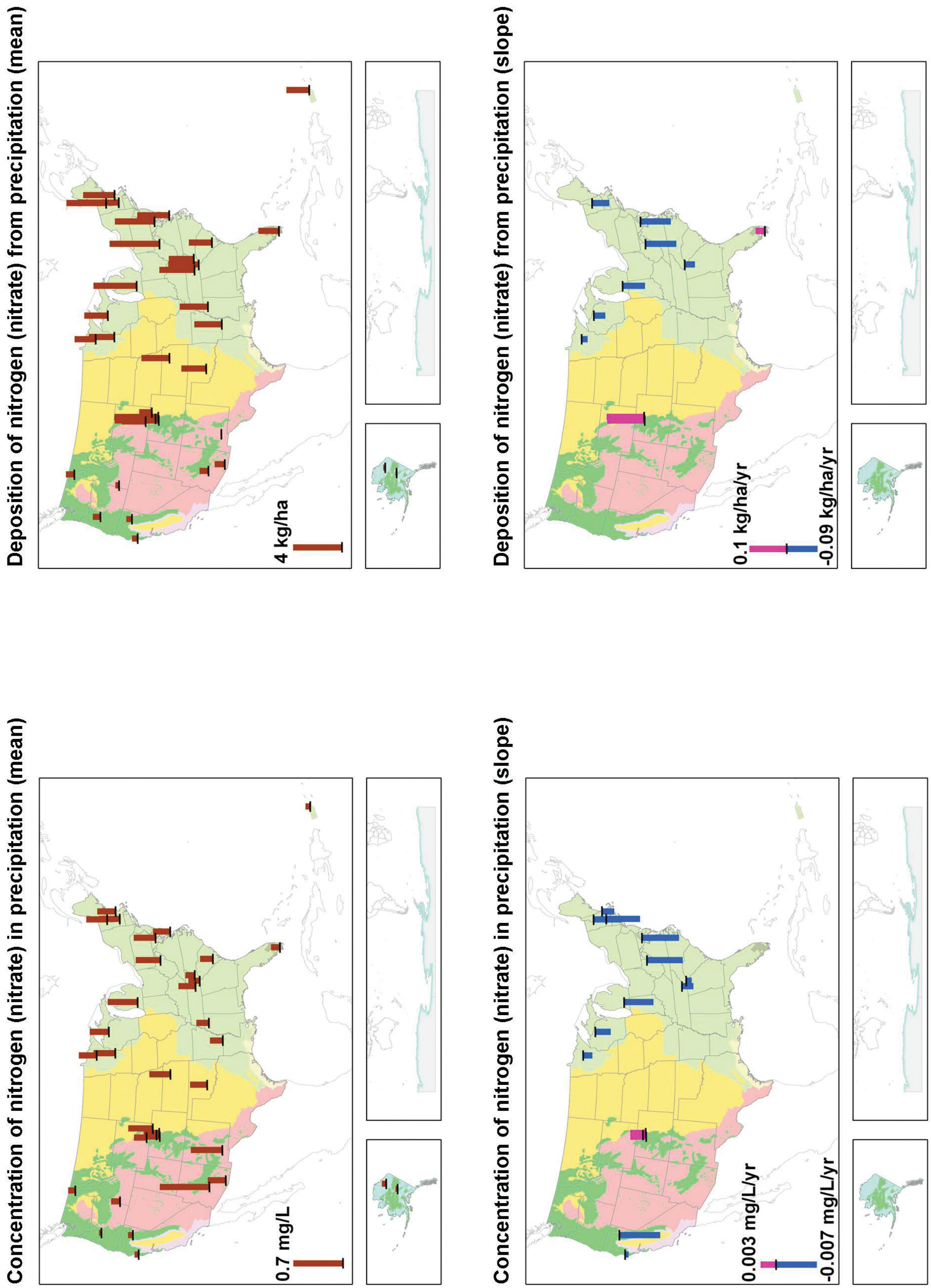


Figure 12-1. Continental patterns in nitrogen (nitrate) from precipitation: concentration (volume-weighted concentration, mg/L) and wet deposition (kg/ha). Top panels: long-term averages where positive values are red and negative values are green. Bottom panels: slopes of significant regression lines ($p < 0.05$) where positive values are pink and negative values are blue. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

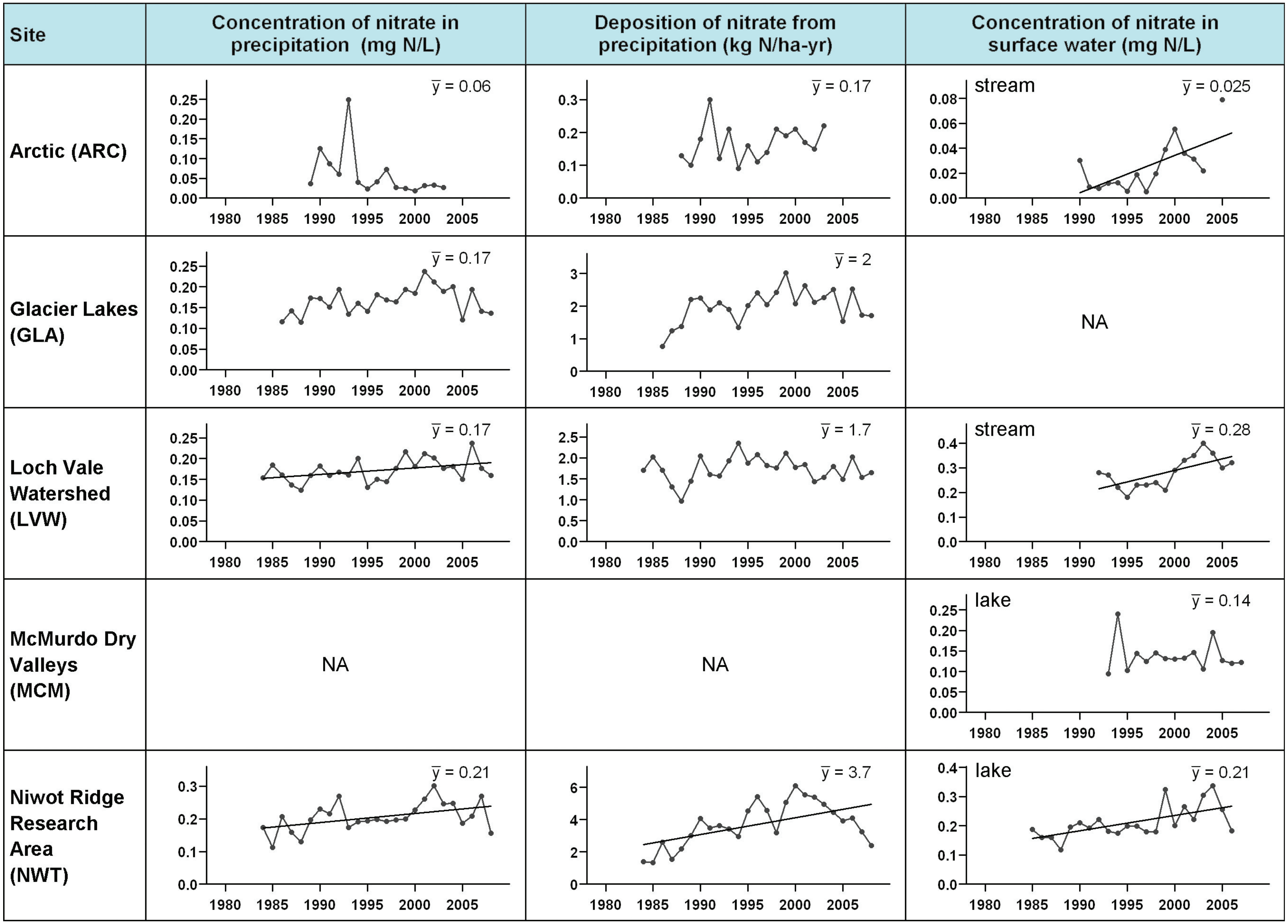


Figure 12-2. Trends for each alpine and arctic site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Arctic (ARC): NS, NS, 0.0030; Glacier Lakes (GLA): NS, NS, NA; Loch Vale Watershed (LVW): 0.0016, NS, 0.0095; McMurdo Dry Valleys (MCM): NA, NA, NS; and Niwot Ridge Research Area (NWT): 0.0028, 0.1035, 0.0052. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

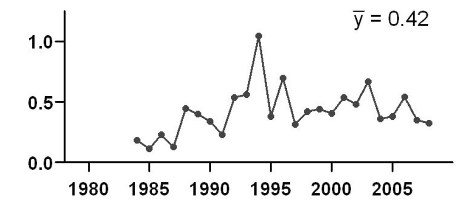
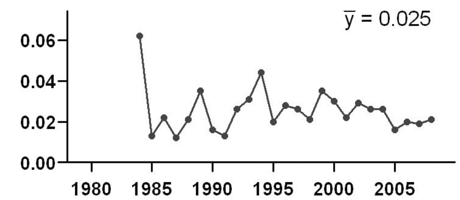
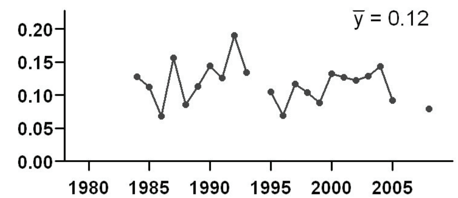
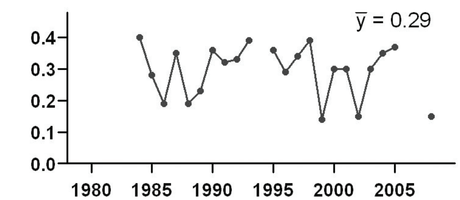
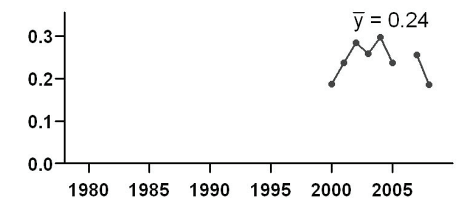
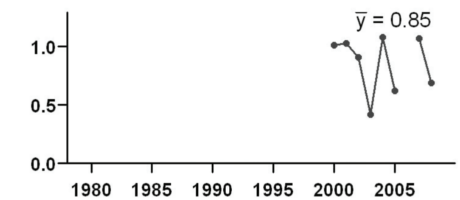
Site	Concentration of nitrate in precipitation (mg N/L)	Deposition of nitrate from precipitation (kg N/ha-yr)	Concentration of nitrate in surface water (mg N/L)
Jornada (JRN)			NA
Reynolds Creek Experimental Watershed (RCE)			NA
Walnut Gulch Experimental Watershed (WGE)			NA

Figure 12-3. Trends for each aridland site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Jornada (JRN): NS, NS, NA; Reynolds Creek Experimental Watershed (RCE): NS, NS, NA; and Walnut Gulch Experimental Watershed (WGE): NS, NS, NA. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

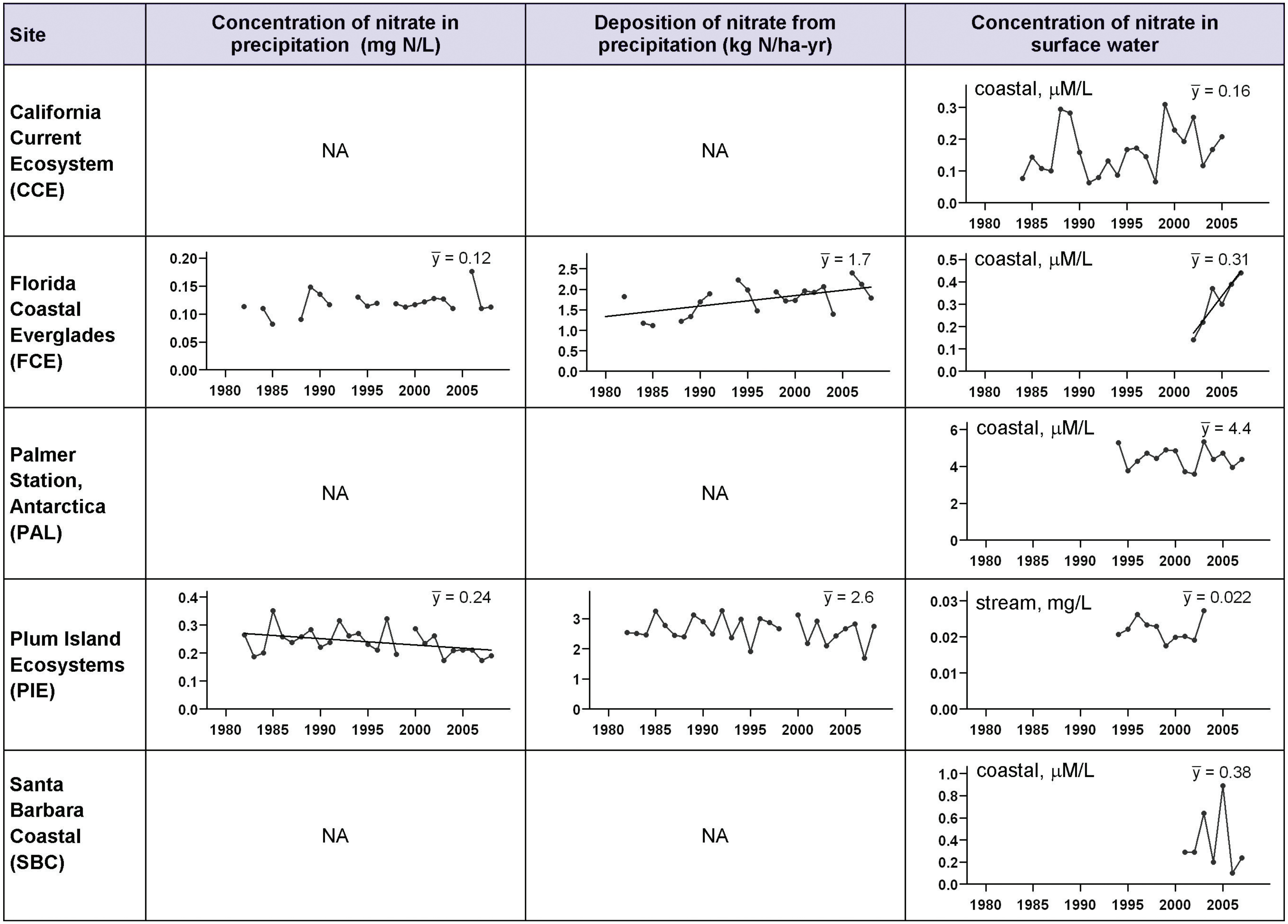


Figure 12-4 (coastal sites) continued next page.

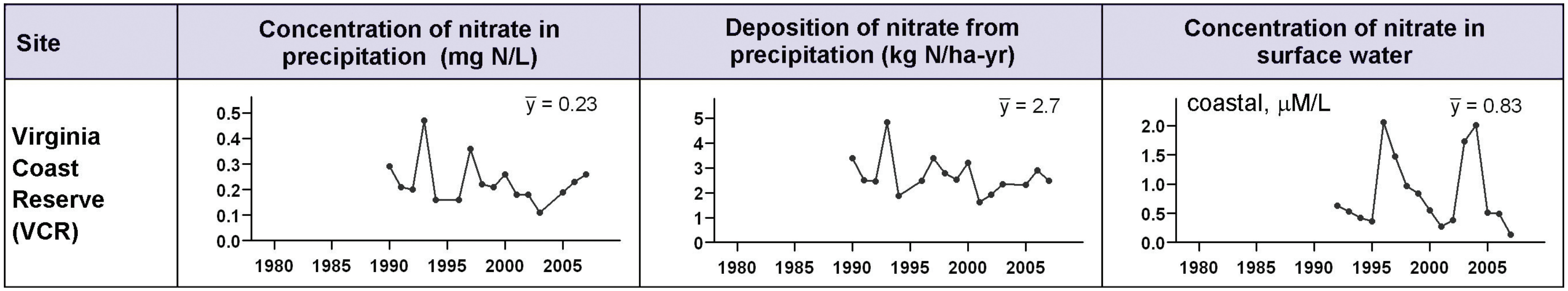


Figure 12-4. Trends for each coastal site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) California Current Ecosystem (CCE): NA, NA, NS; Florida Coastal Everglades (FCE): NS, 0.0259, 0.0554; Palmer Station, Antarctica (PAL): NA, NA, NS; Plum Island Ecosystems (PIE): -0.0022, NS, NS; Santa Barbara Coastal (SBC): NA, NA, NS; and Virginia Coast Reserve (VCR): NS, NS, NS. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

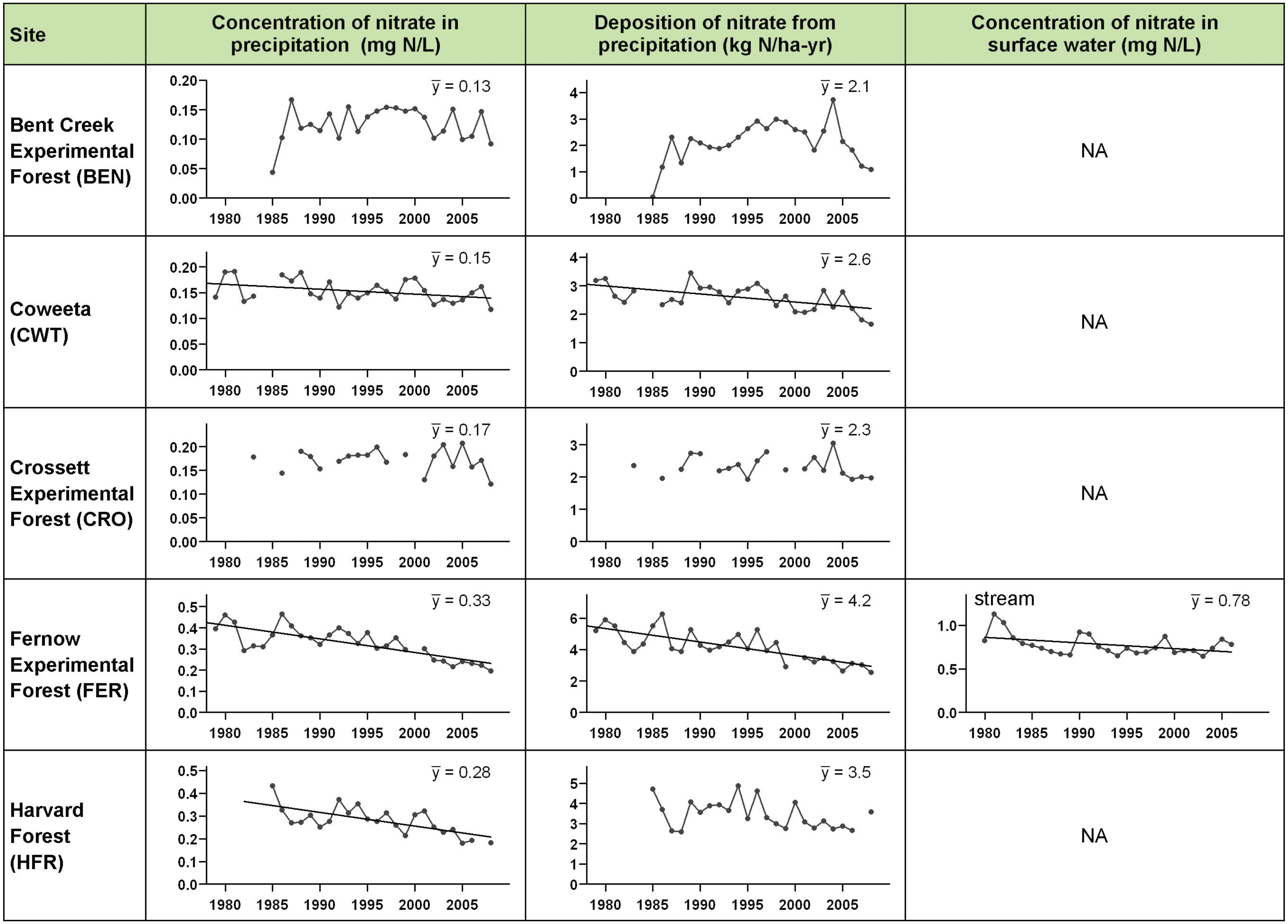


Figure 12-5 (eastern forest sites) continued next page.

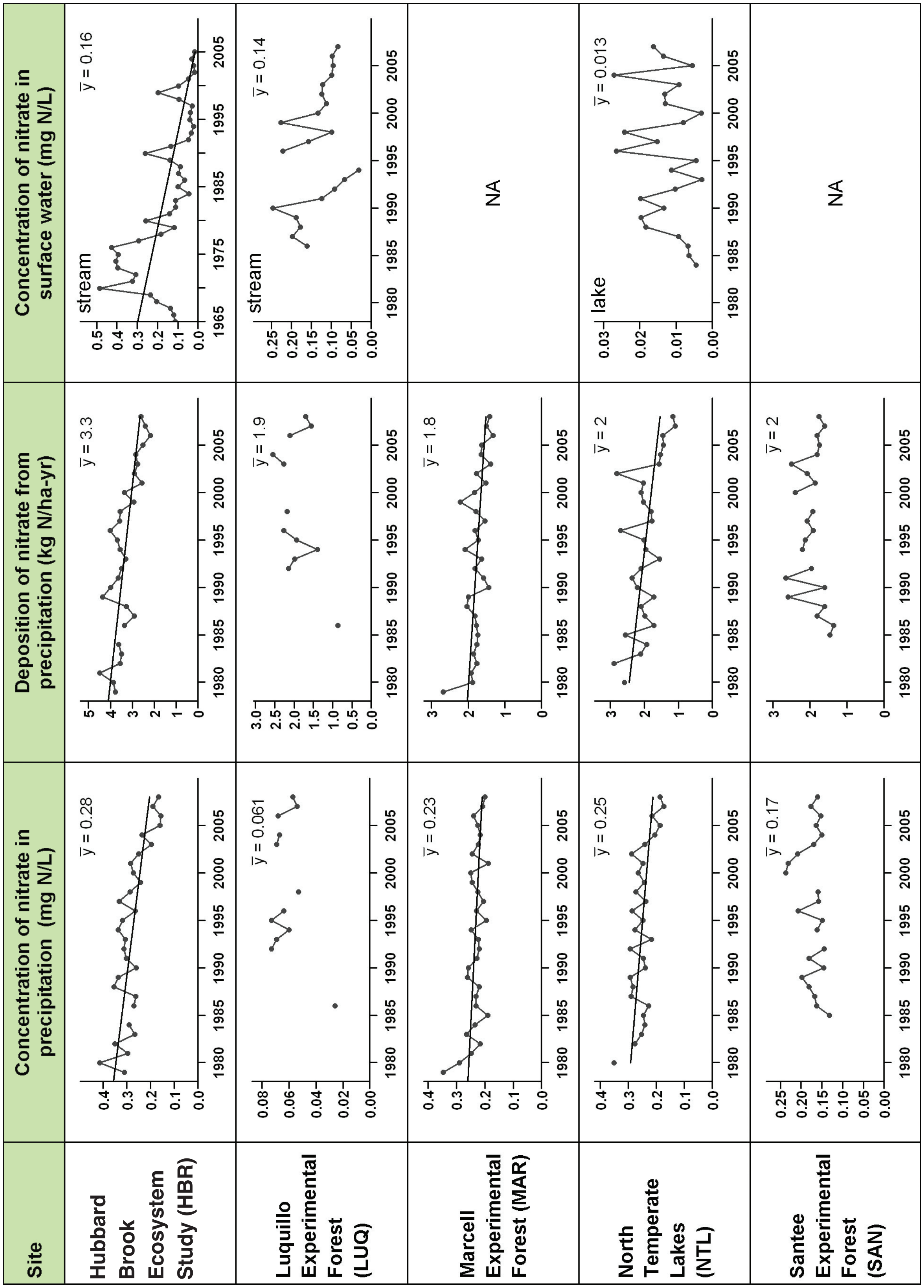


Figure 12-5 (eastern forest sites) continued next page.

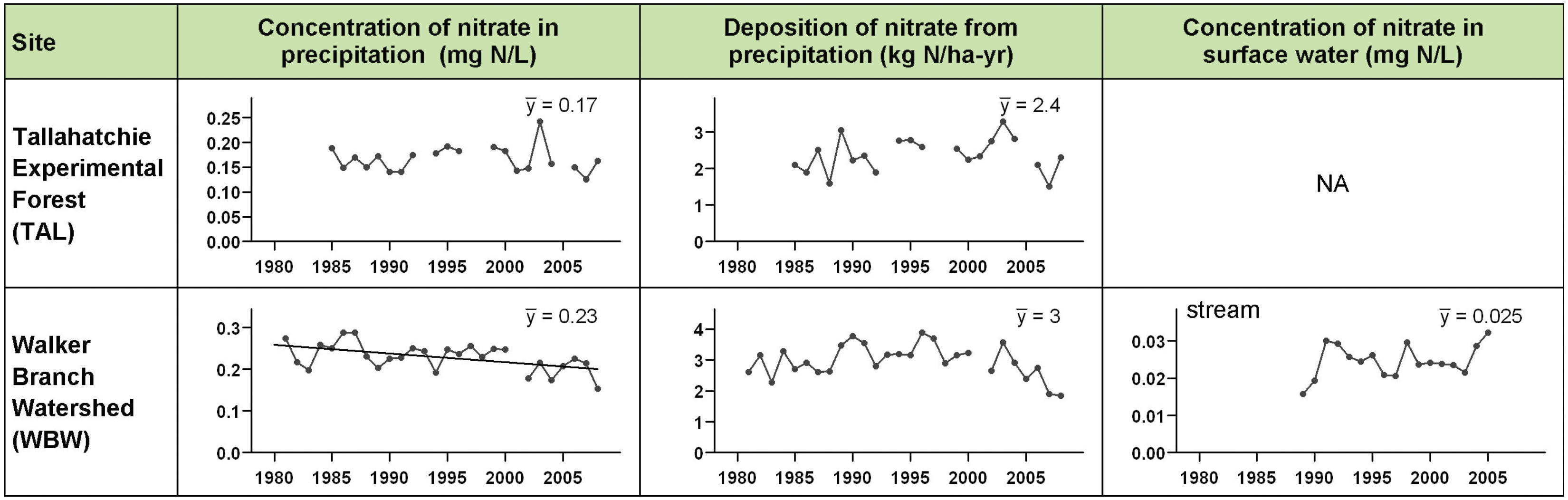


Figure 12-5. Trends for each eastern forest site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Bent Creek Experimental Forest (BEN): NS, NS, NA; Crossett Experimental Forest (CRO): NS, NS, NA; Coweeta (CWT): -0.0010, -0.0282, NA; Fernow Experimental Forest (FER): -0.0064, -0.0857, -0.0064; Hubbard Brook Ecosystem Study (HBR): -0.0050, -0.0483, -0.0071; Harvard Forest (HFR): -0.0061, NS, NA; Luquillo Experimental Forest (LUQ): NS, NS, NS; Marcell Experimental Forest (MAR): -0.0017, -0.0170, NA; North Temperate Lakes (NTL): -0.0028, -0.0324, NS; Santee Experimental Forest (SAN): NS, NS, NA; Tallahatchie Experimental Forest (TAL): NS, NS, NA; and Walker Branch Watershed (WBW): -0.0021, NS, NS. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

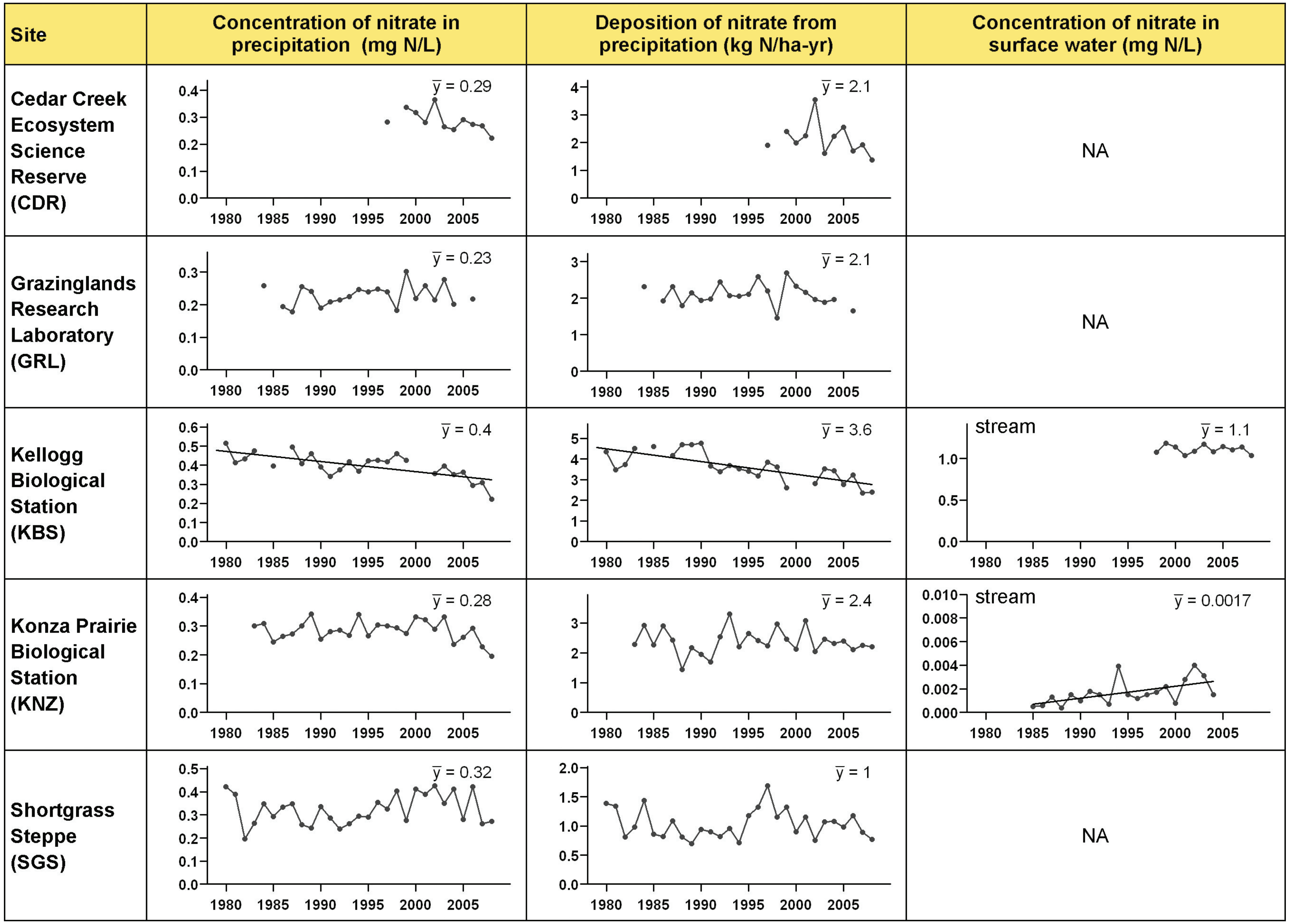


Figure 12-6. Trends for each temperate grassland and savanna site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Cedar Creek Ecosystem Science Reserve (CDR): NS, NS, NA; Grazinglands Research Laboratory (GRL): NS, NS, NA; Kellogg Biological Station (KBS): -0.0053, -0.0620, NS; Konza Prairie Biological Station (KNZ): NS, NS, 0.0001; and Shortgrass Steppe (SGS): NS, NS, NA. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

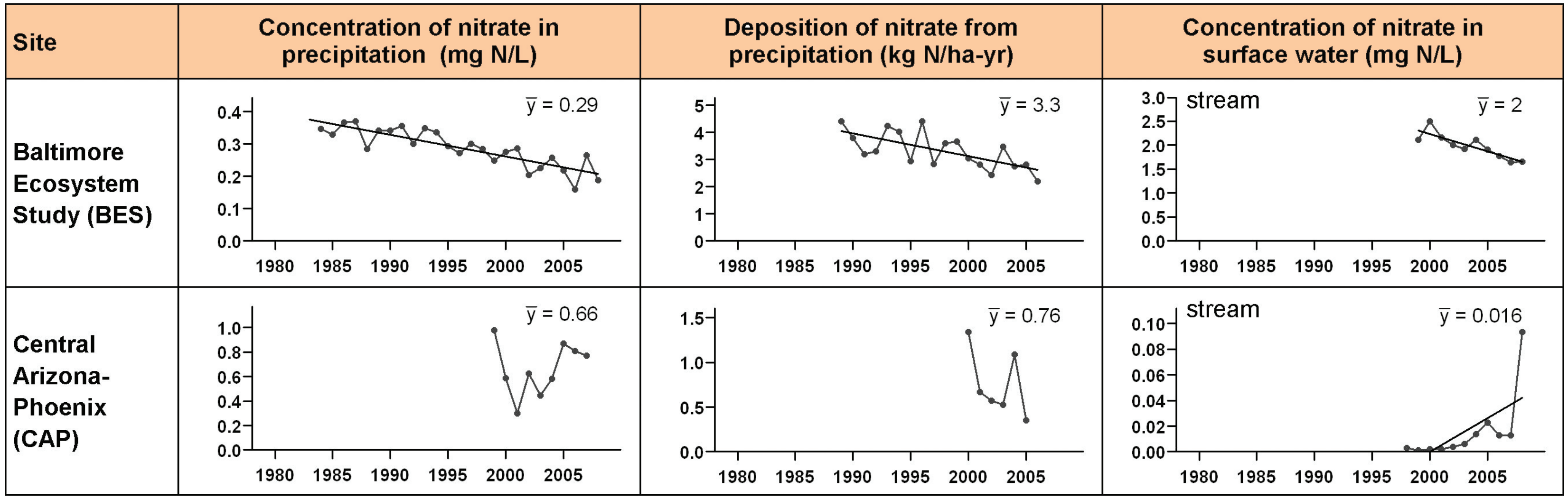


Figure 12-7. Trends for each urban site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NS = not significant) Baltimore Ecosystem Study (BES): -0.0067, -0.0841, -0.0733 and Central Arizona-Phoenix (CAP): NS, NS, 0.0053. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

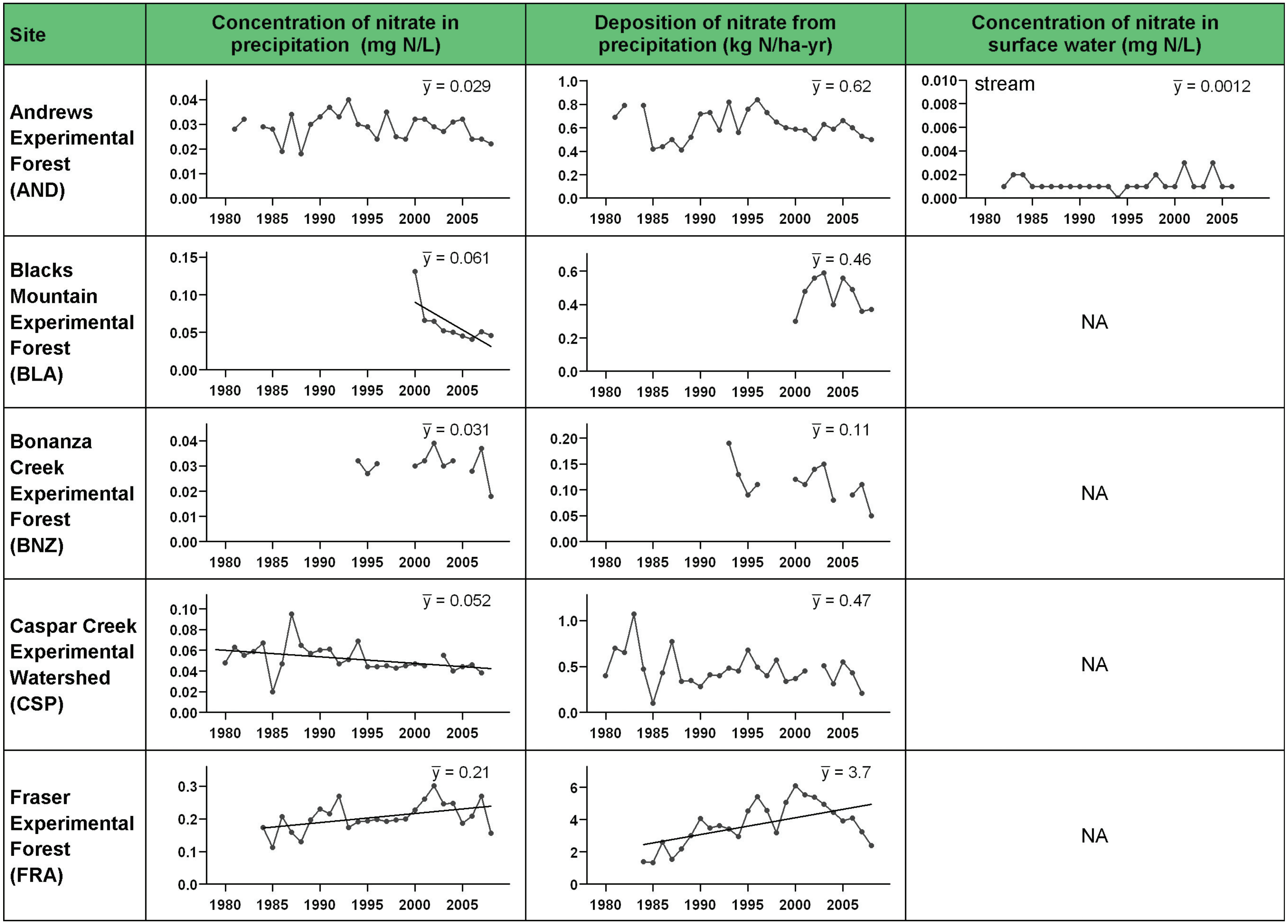


Figure 12-8 (western forest sites) continued next page.

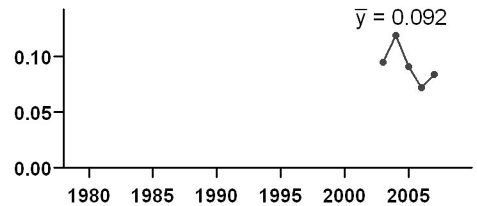
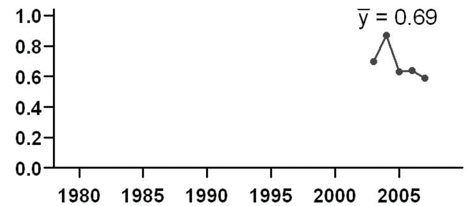
Site	Concentration of nitrate in precipitation (mg N/L)	Deposition of nitrate from precipitation (kg N/ha-yr)	Concentration of nitrate in surface water (mg N/L)
Priest River Experimental Forest (PRI)			NA

Figure 12-8. Trends for each western forest site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) H.J. Andrews Experimental Forest (AND): NS, NS, NS; Blacks Mountain Experimental Forest (BLA): -0.0073, NS, NA; Bonanza Creek Experimental Forest (BNZ): NS, NS, NA; Caspar Creek Experimental Watershed (CSP): -0.0006, NS, NA; Fraser Experimental Forest (FRA): 0.0028, 0.1035, NA; and Priest River Experimental Forest (PRI): NS, NS, NA. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

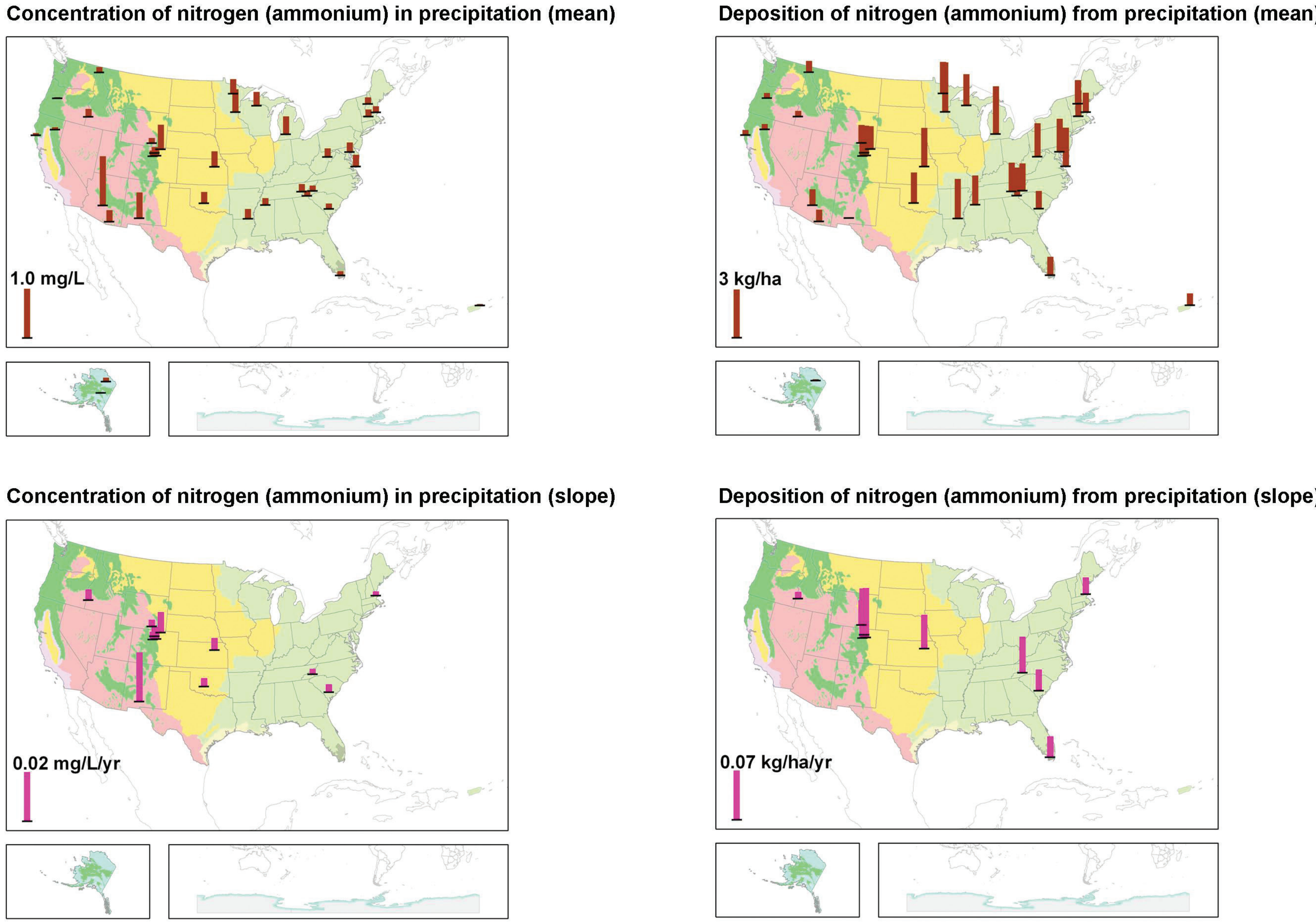


Figure 12-9. Continental patterns in nitrogen (ammonium) from precipitation: concentration (volume-weighted concentration, mg/L) and wet deposition (kg/ha). Top panels: long-term averages where positive values are red and negative values are green. Bottom panels: slopes of significant regression lines ($p < 0.05$) where positive values are pink and negative values are blue. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

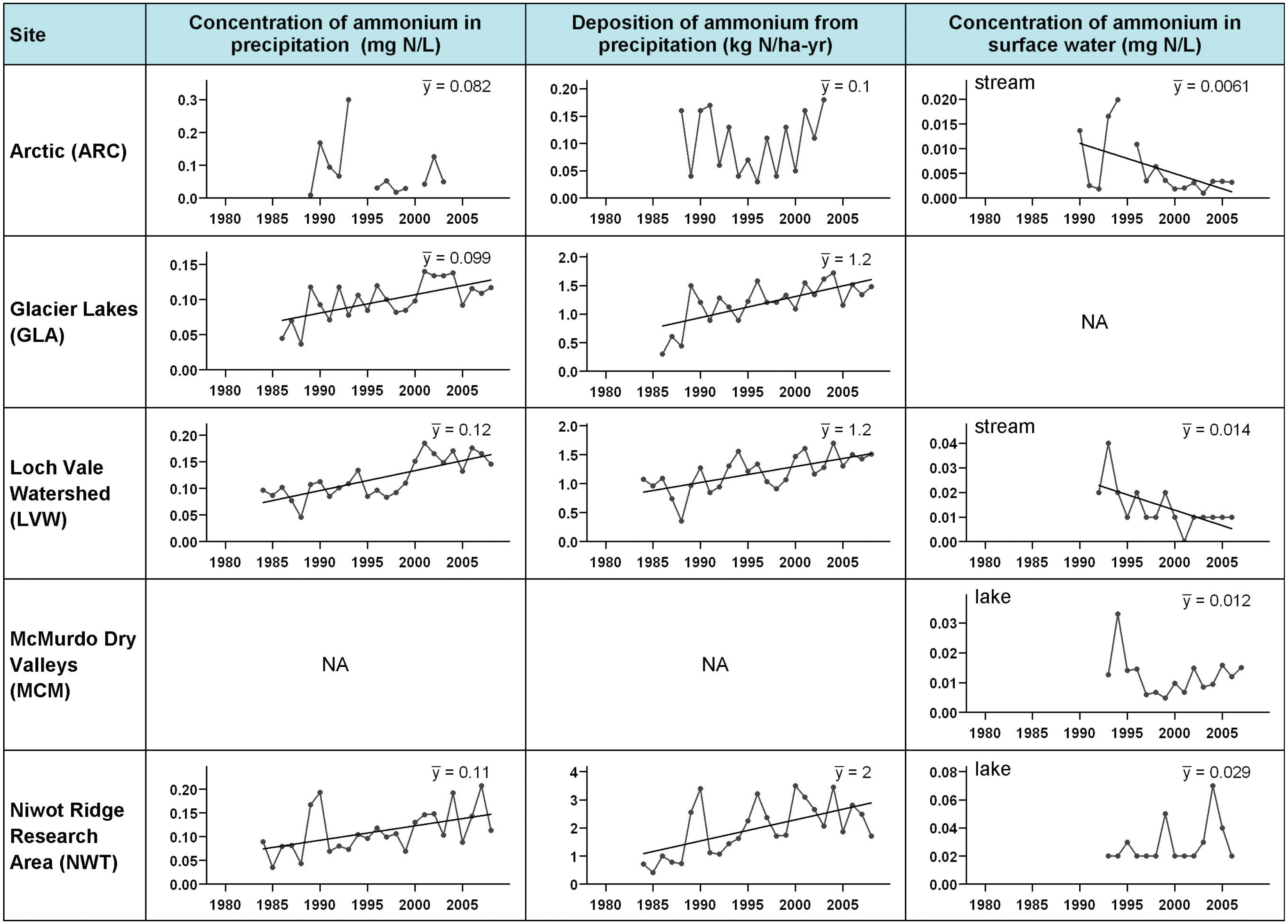


Figure 12-10. Trends for each alpine and arctic site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Arctic (ARC): NS, NS, -0.0006); Glacier Lakes (GLA): 0.0026, 0.0371, NA; Loch Vale Watershed (LVW): 0.0038, 0.0273, -0.0013; McMurdo Dry Valleys (MCM): NA, NA, NS; and Niwot Range Research Area (NWT): 0.0030, 0.0748, NS. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

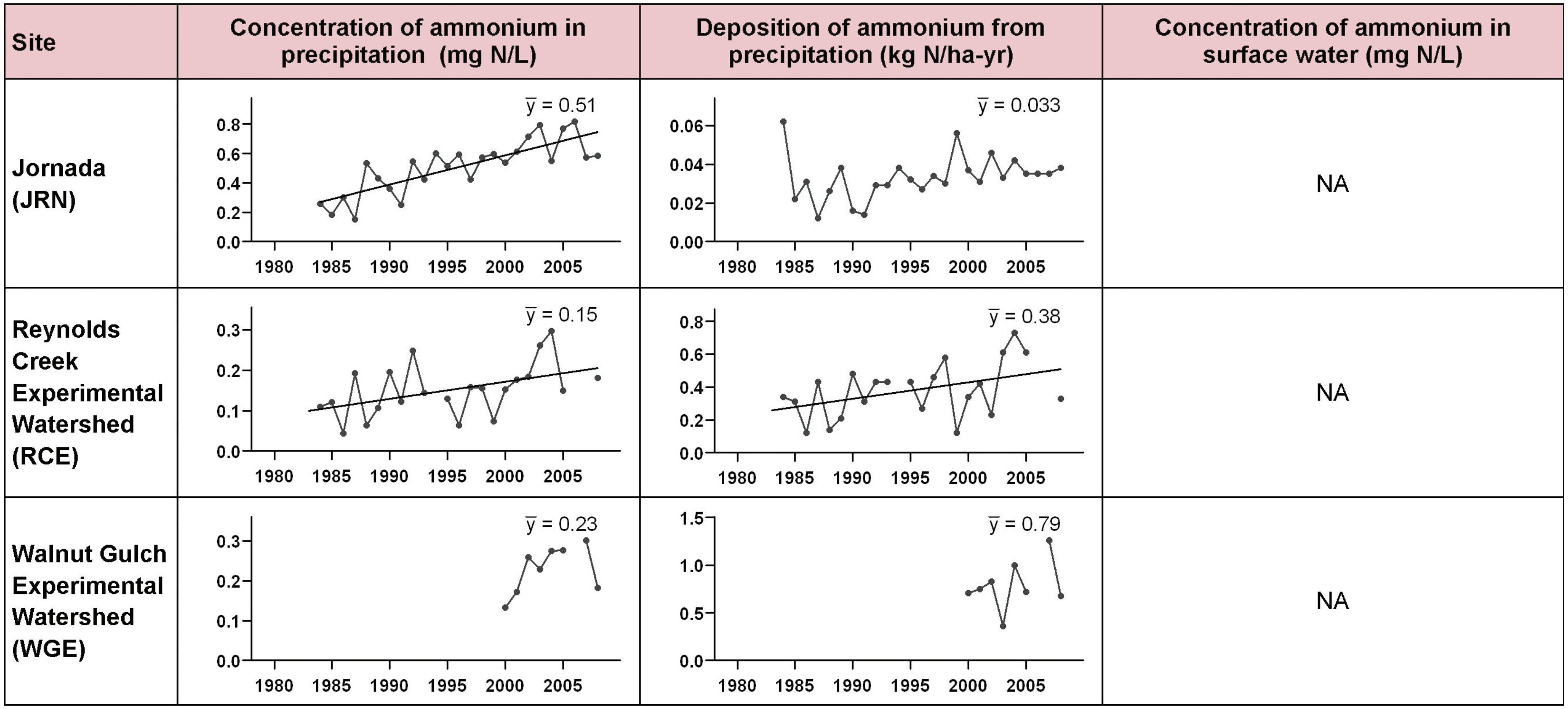


Figure 12-11. Trends for each aridland site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Jornada (JRN): 0.0199, NS, NA; Reynolds Creek Experimental Watershed (RCE): 0.0042, 0.0100, NA; and Walnut Gulch Experimental Watershed (WGE): NS, NS, NA. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

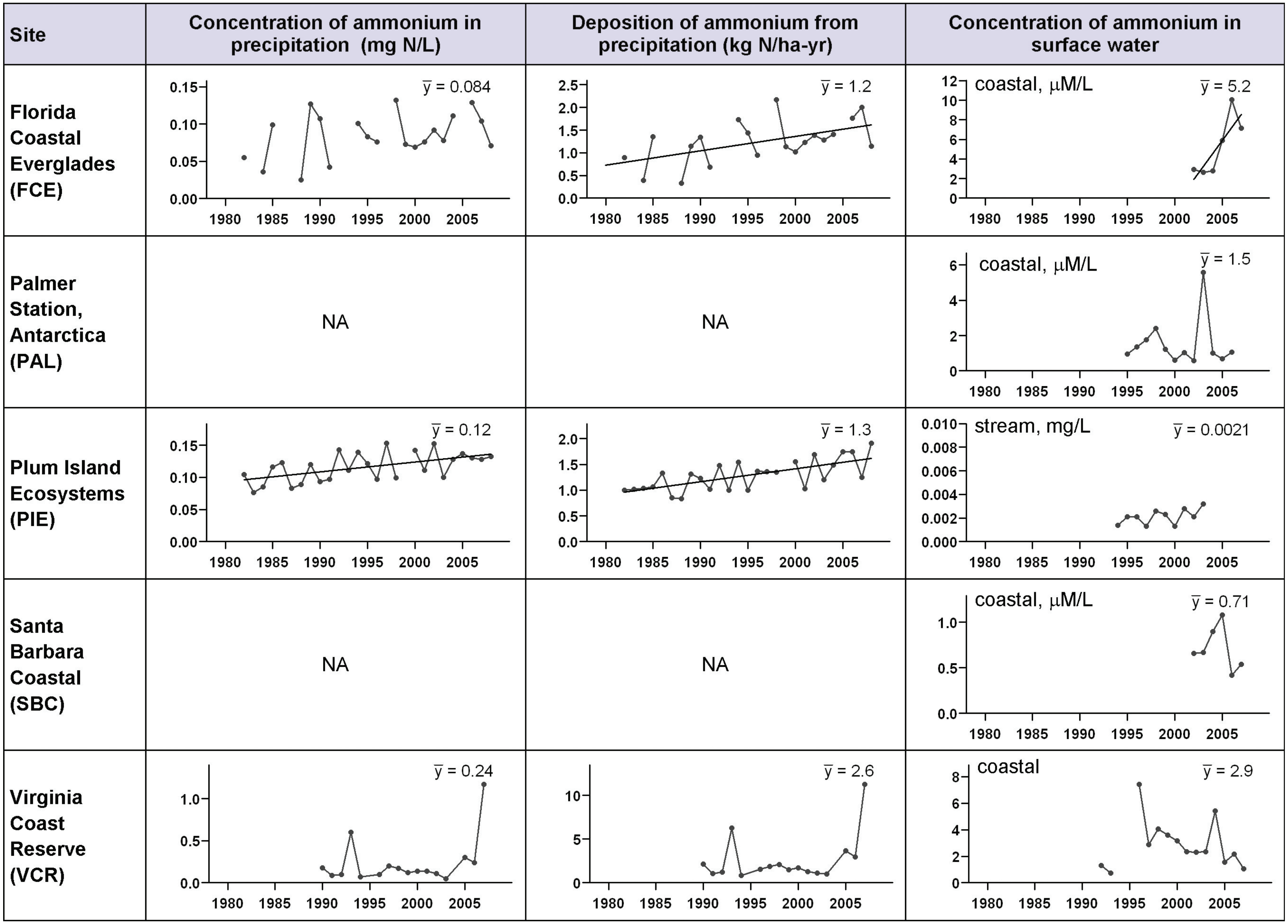


Figure 12-12. Trends for each coastal site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Florida Coastal Everglades (FCE): NS, 0.0317, 1.3249; Palmer Station, Antarctica (PAL): NA, NA, NS; Plum Island Ecosystems (PIE): 0.0015, 0.0250, NS; Santa Barbara Coastal (SBC): NA, NA, NS; and Virginia Coast Reserve (VCR): NS, NS, NS. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

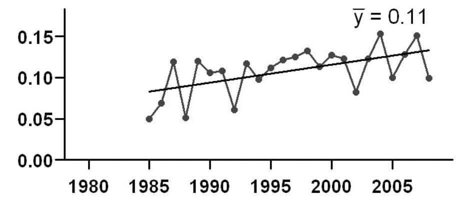
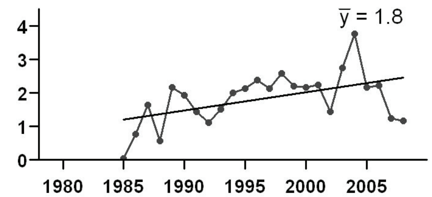
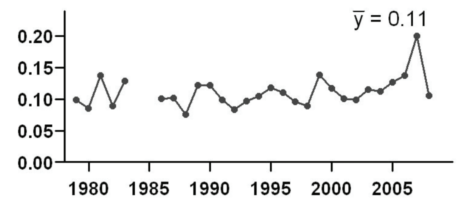
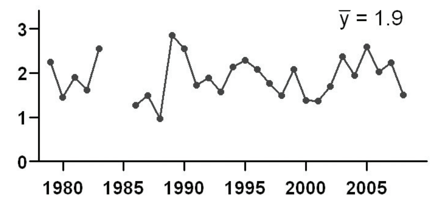
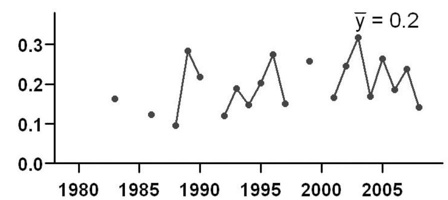
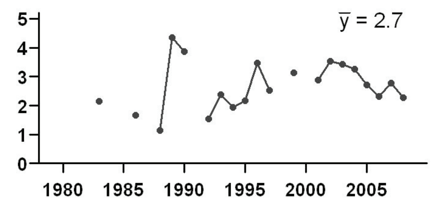
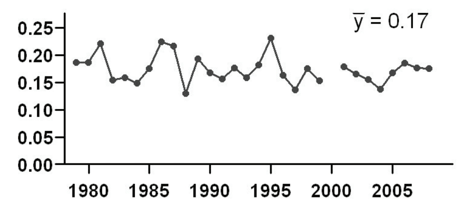
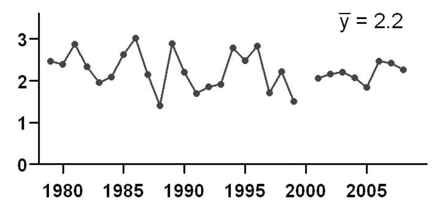
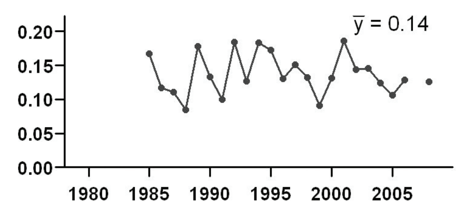
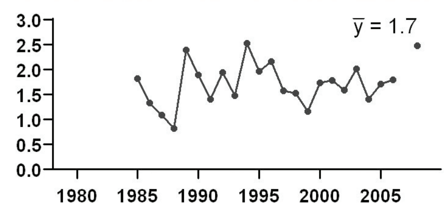
<table>
<tr><th>Site</th><th>Concentration of ammonium in precipitation (mg N/L)</th><th>Deposition of ammonium from precipitation (kg N/ha-yr)</th><th>Concentration of ammonium in surface water (mg N/L)</th></tr>
<tr><td>Bent Creek Experimental Forest (BEN)</td><td></td><td></td><td>NA</td></tr>
<tr><td>Coweeta (CWT)</td><td></td><td></td><td>NA</td></tr>
<tr><td>Crossett Experimental Forest (CRO)</td><td></td><td></td><td>NA</td></tr>
<tr><td>Fernow Experimental Forest (FER)</td><td></td><td></td><td>NA</td></tr>
<tr><td>Harvard Forest (HFR)</td><td></td><td></td><td>NA</td></tr>
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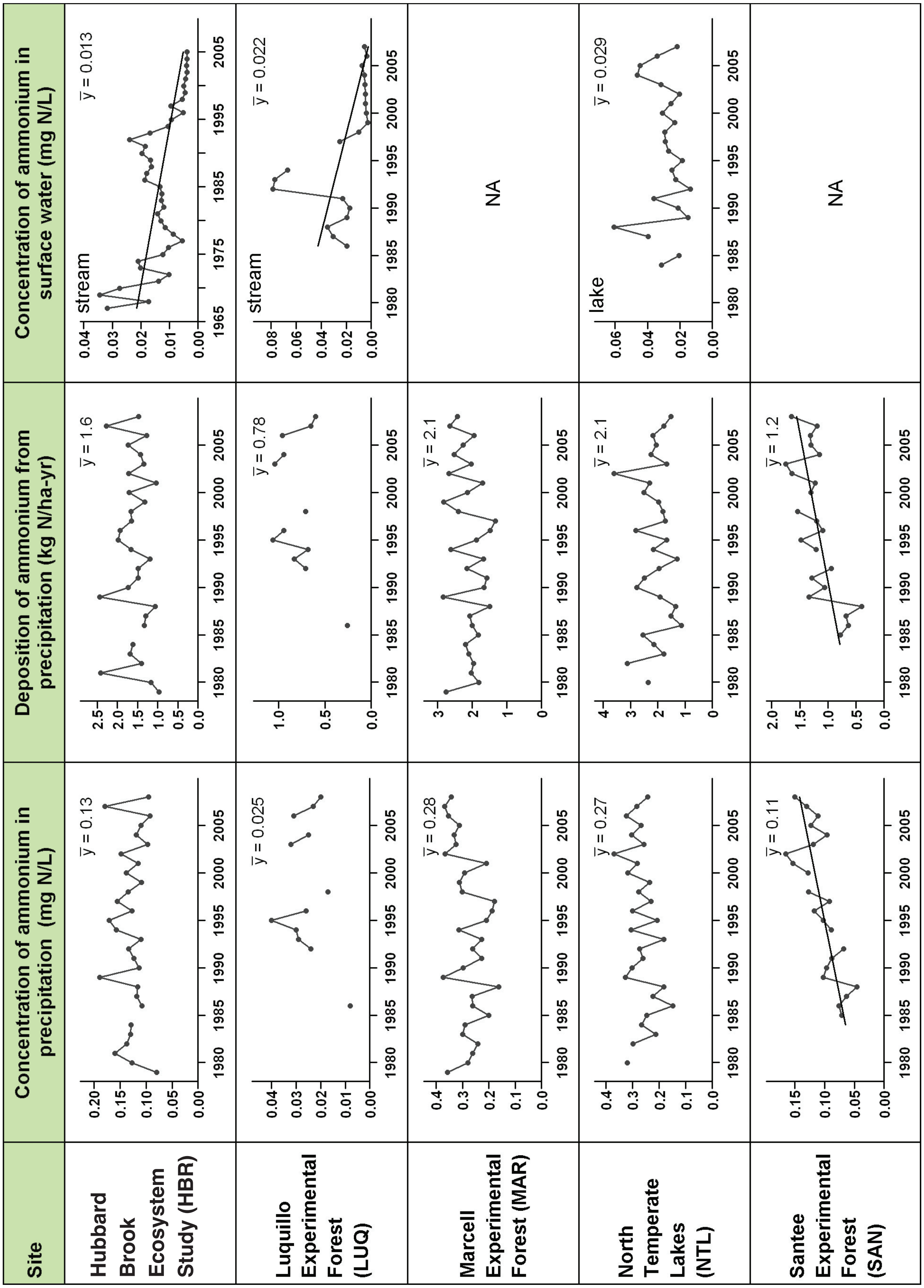
Figure 12-13 (eastern forest sites) continued next page.



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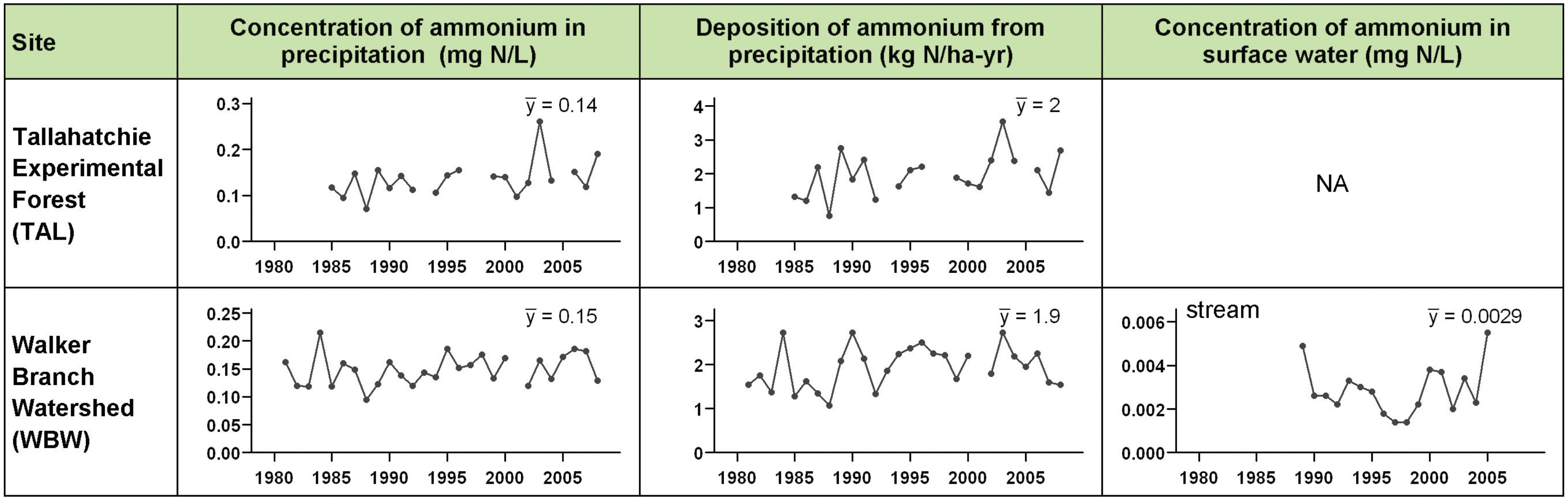

Figure 12-13. Trends for each eastern forest site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Bent Creek Experimental Forest (BEN): 0.0022, 0.0545, NA; Crossett Experimental Forest (CRO): NS, NS, NA; Coweeta (CWT): NS, NS, NA; Fernow Experimental Forest (FER): NS, NS, NA; Hubbard Brook Ecosystem Study (HBR): NS, NS, -0.0004; Harvard Forest (HFR): NS, NS, NA; Luquillo Experimental Forest (LUQ): NS, NS, -0.0019; Marcell Experimental Forest (MAR): NS, NS, NA; North Temperate Lakes (NTL): NS, NS, NS; Santee Experimental Forest (SAN): 0.0032, 0.0320, NA; Tallahatchie Experimental Forest (TAL): NS, NS, NA; and Walker Branch Watershed (WBW): NS, NS, NS. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

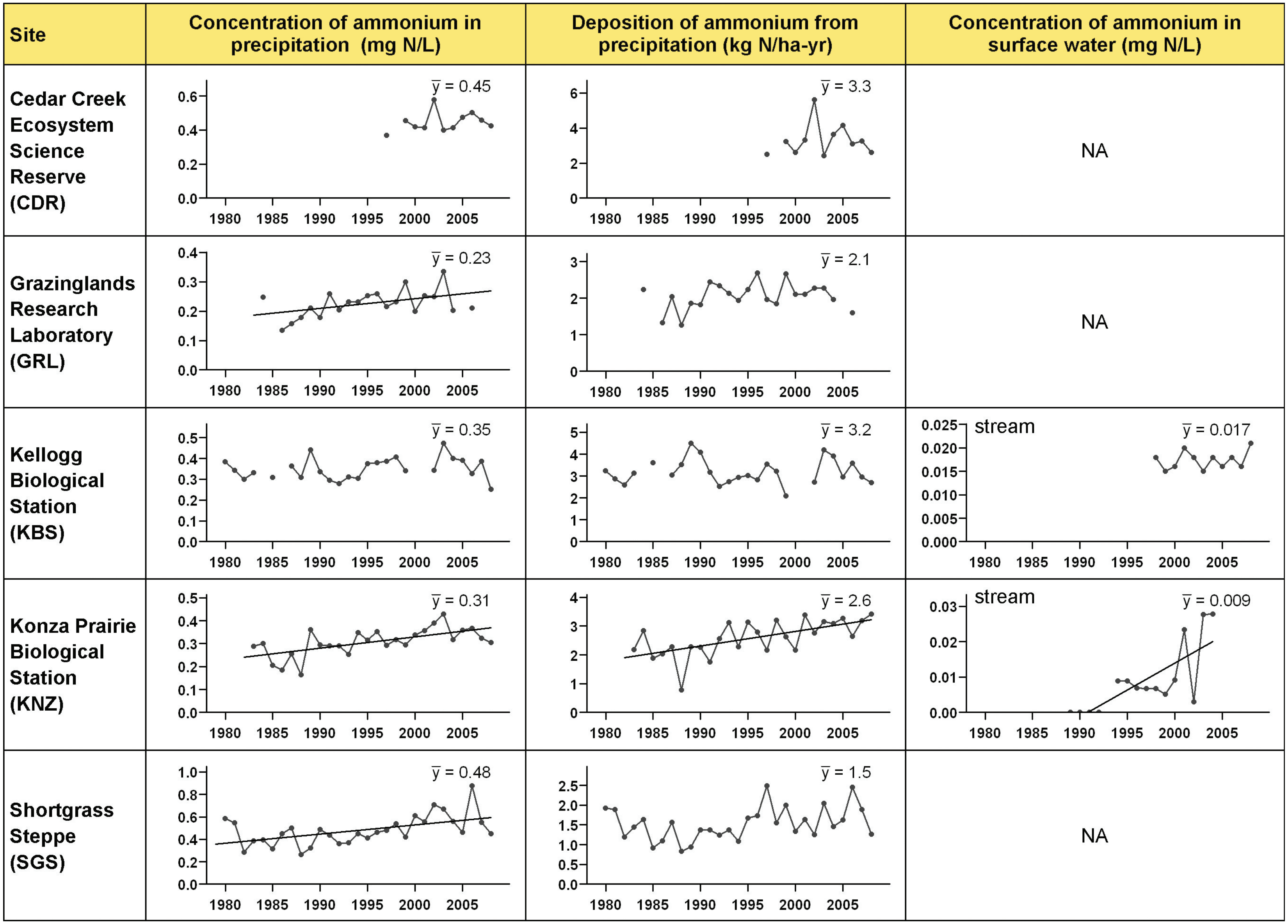

Figure 12-14. Trends for each temperate grassland and savanna site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Cedar Creek Ecosystem Science Reserve (CDR): NS, NS, NA; Grazinglands Research Laboratory (GRL): 0.0033, NS, NA; Kellogg Biological Station (KBS): NS, NS, NS; Kona Prairie Biological Station (KNZ): 0.0049, 0.0511, 0.0015; and Shortgrass Steppe (SGS): 0.0081, NS, NA. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

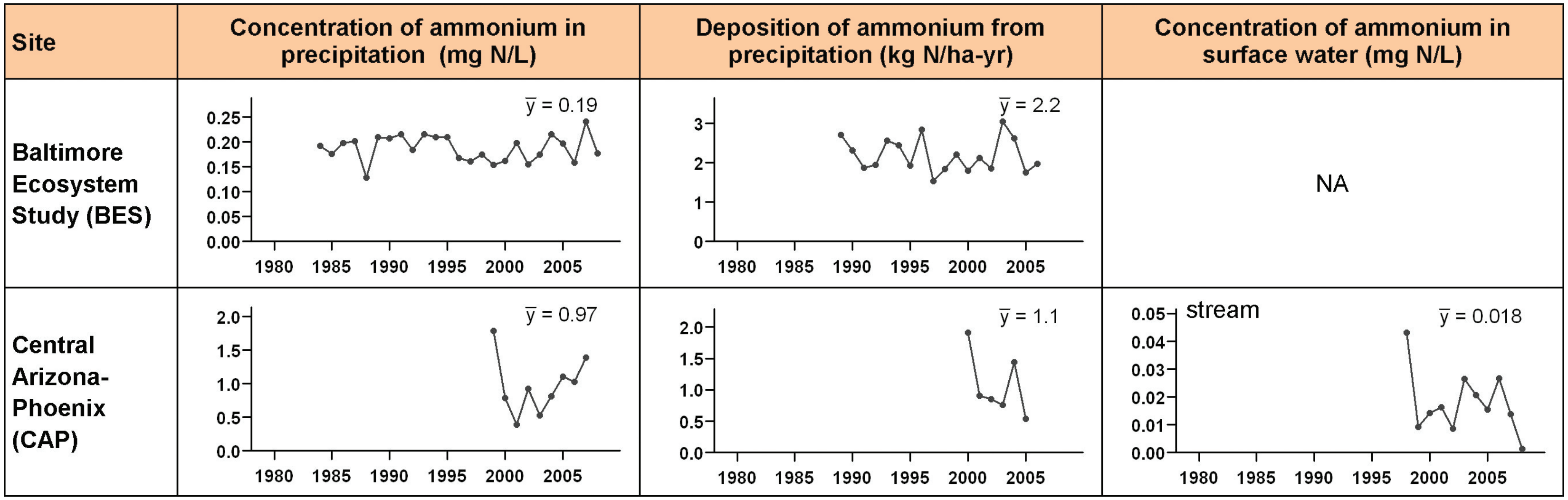

Figure 12-15. Trends for each urban site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Baltimore Ecosystem Study (BES): NS, NS, NA and Caspar Creek Experimental Watershed (CAP): NS, NS, NS. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

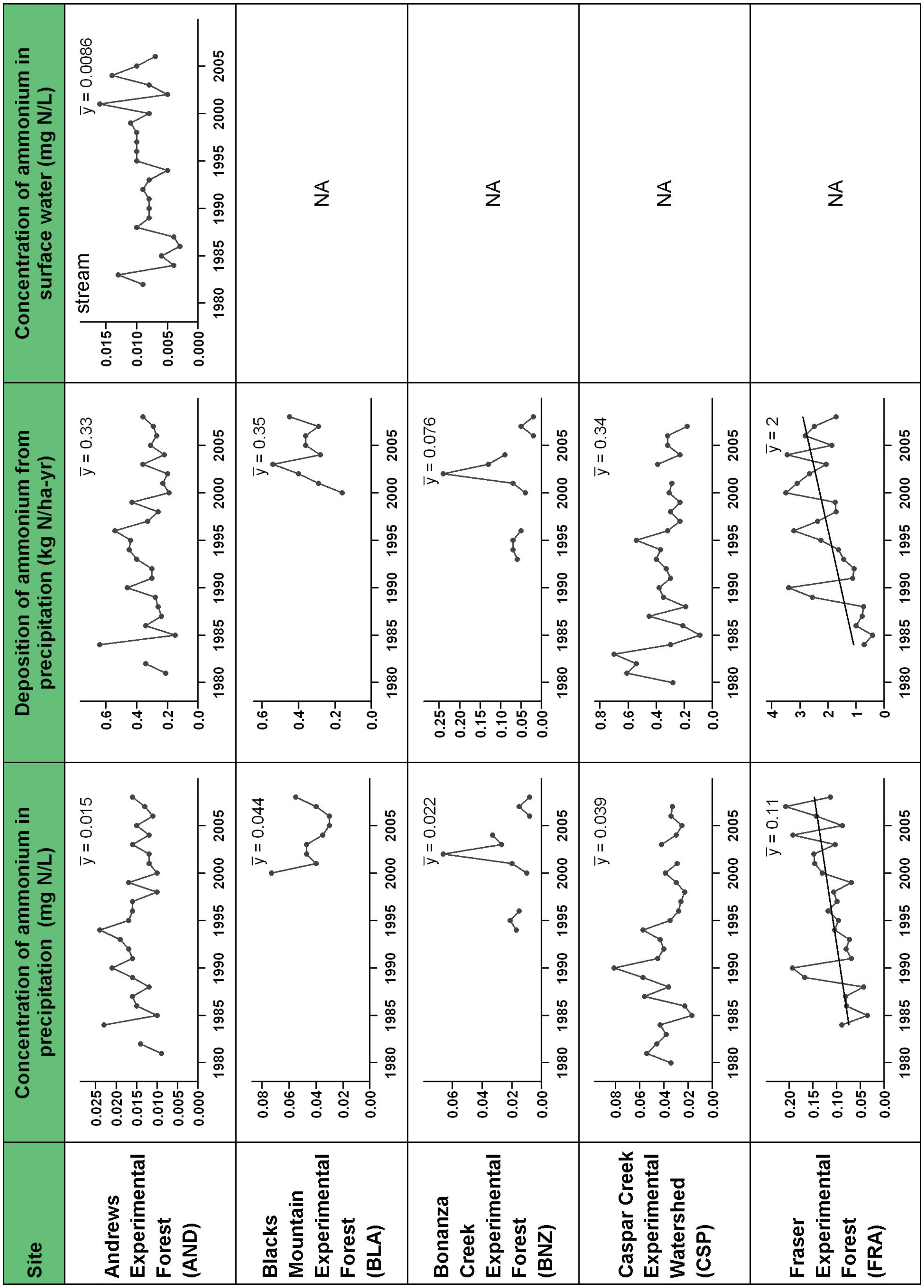

Figure 12-16 (western forest sites) continued next page.

<table>
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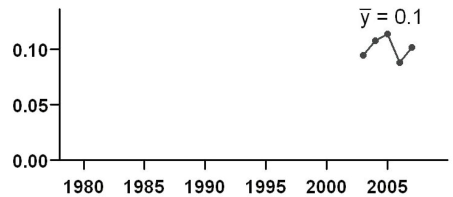
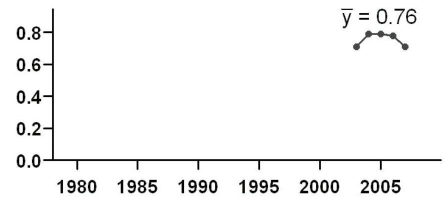
<tr><td>Priest River Experimental Forest (PRI)</td><td>
</td><td>
</td><td>NA</td></tr>
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Figure 12-16. Trends for each western forest site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) H.J. Andrews Experimental Forest (AND): NS, NS, NS; Blacks Mountain Experimental Forest (BLA): NS, NS, NA; Bonanza Creek Experimental Forest (BNZ): NS, NS, NA; Caspar Creek Experimental Watershed (CSP): NS, NS, NA; Fraser Experimental Forest (FRA): 0.0030, 0.0748, NA; and Priest River Experimental Forest (PRI): NS, NS, NA. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

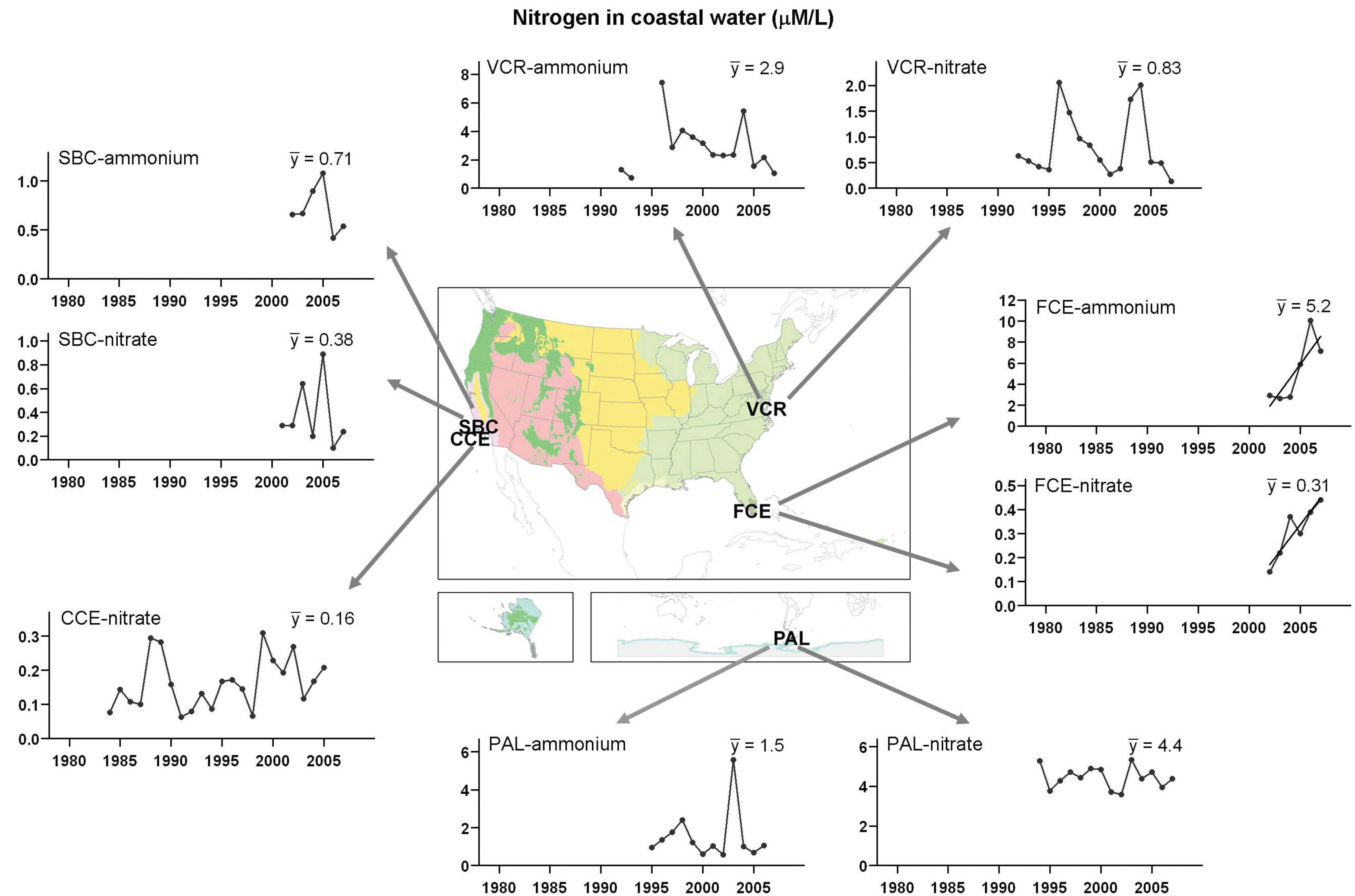


Figure 12-17. Concentration of nitrogen (ammonium and nitrate, µM/L) in coastal water through time at five sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Florida Coastal Everglades (FCE) (1.32 ammonium and 0.06 nitrate). Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

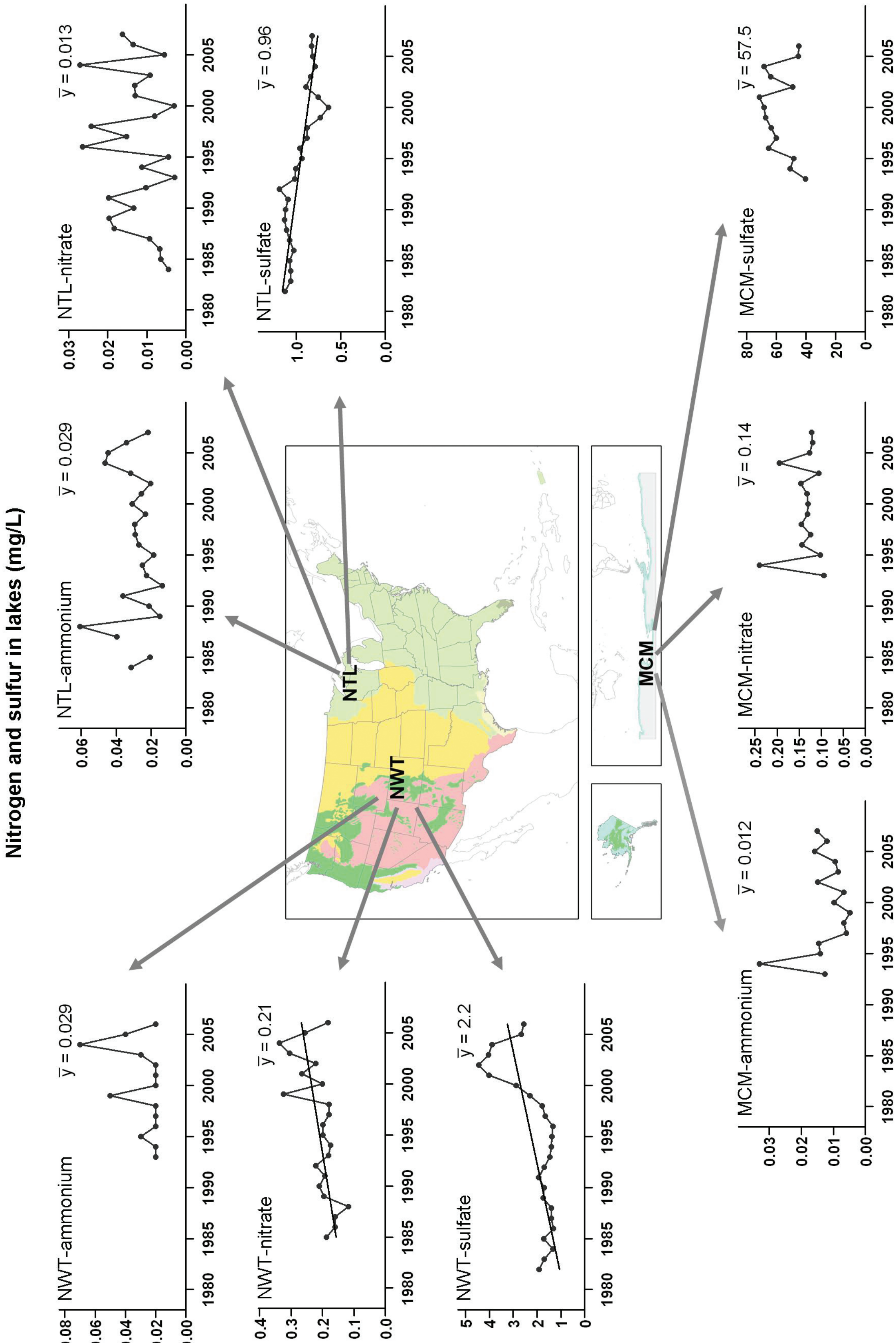


Figure 12-18. Concentrations of nitrogen (ammonium and nitrate, mg/L) and sulfur (sulfate, mg/L) in lakes through time at three sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Niwot Ridge Research Area (NWT) (0.005 nitrate, 0.091 sulfate) and North Temperate Lakes (NTL) (-0.016 sulfate). Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

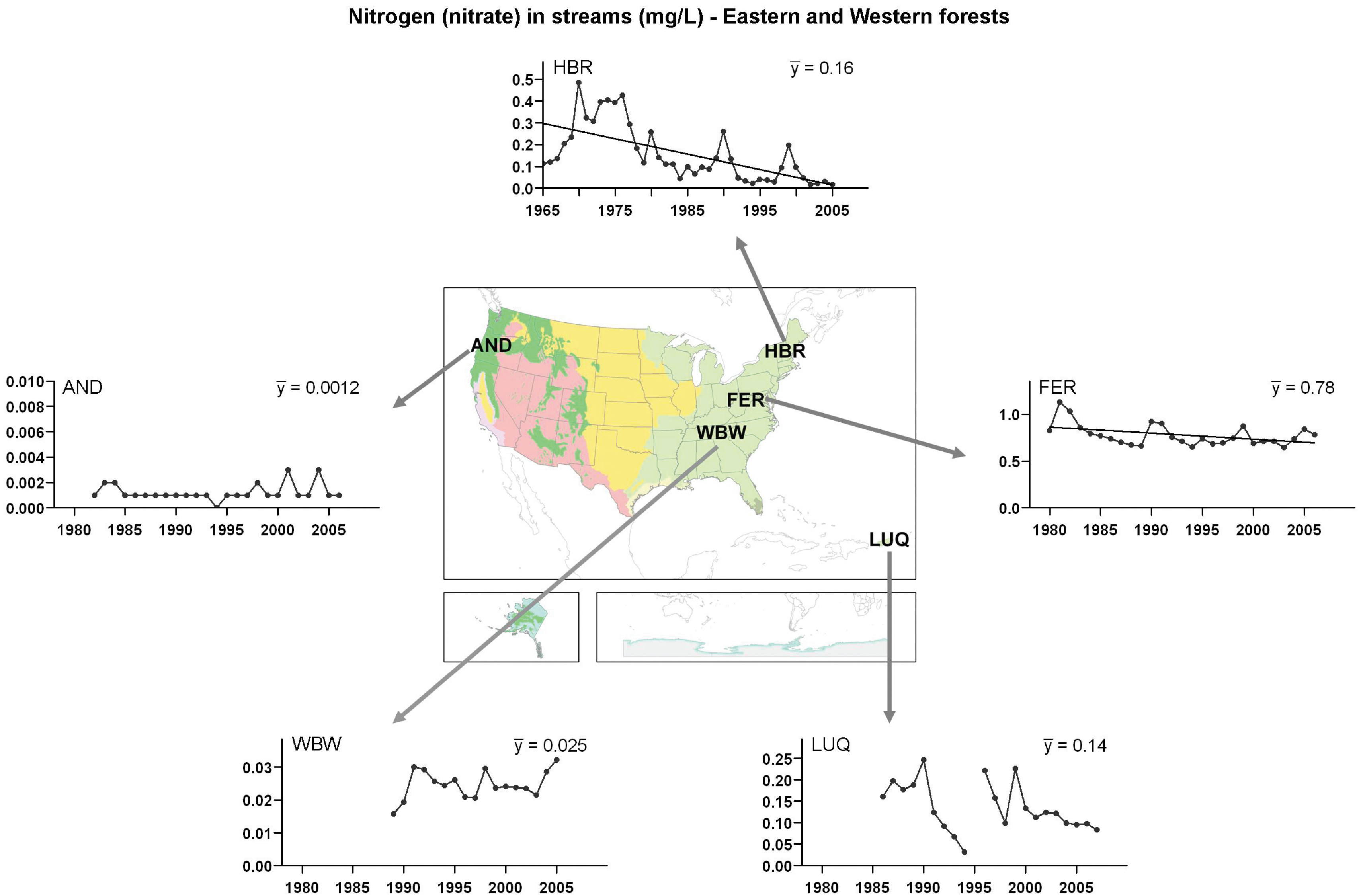


Figure 12-19. Concentration of nitrogen (nitrate, mg/L) in streams through time at four eastern forest sites and one western forest site. A simple line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Fernow Experimental Forest (FER) (-0.006) and Hubbard Brook Ecosystem Study (HBR) (-0.007). Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

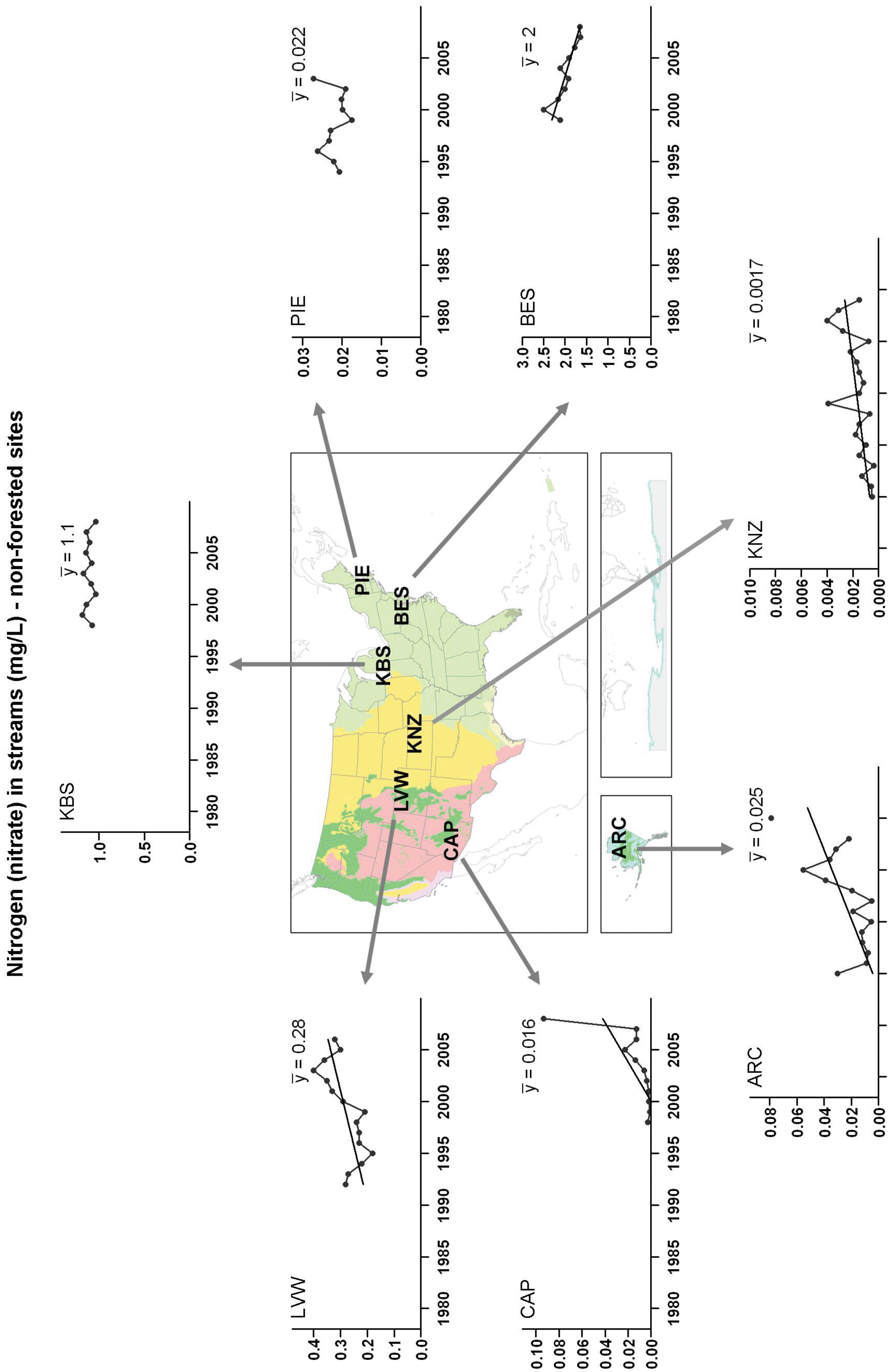


Figure 12-20. Concentration of nitrogen (nitrate, mg/L) in streams through time at seven nonforested sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Arctic (ARC) (0.0030), Baltimore Ecosystem Study (BES) (-0.0733), Central Arizona-Phoenix (CAP) (0.0053), Konza Prairie Biological Station (KNZ) (0.0001), and Loch Vale Watershed (LVW) (0.0095). Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

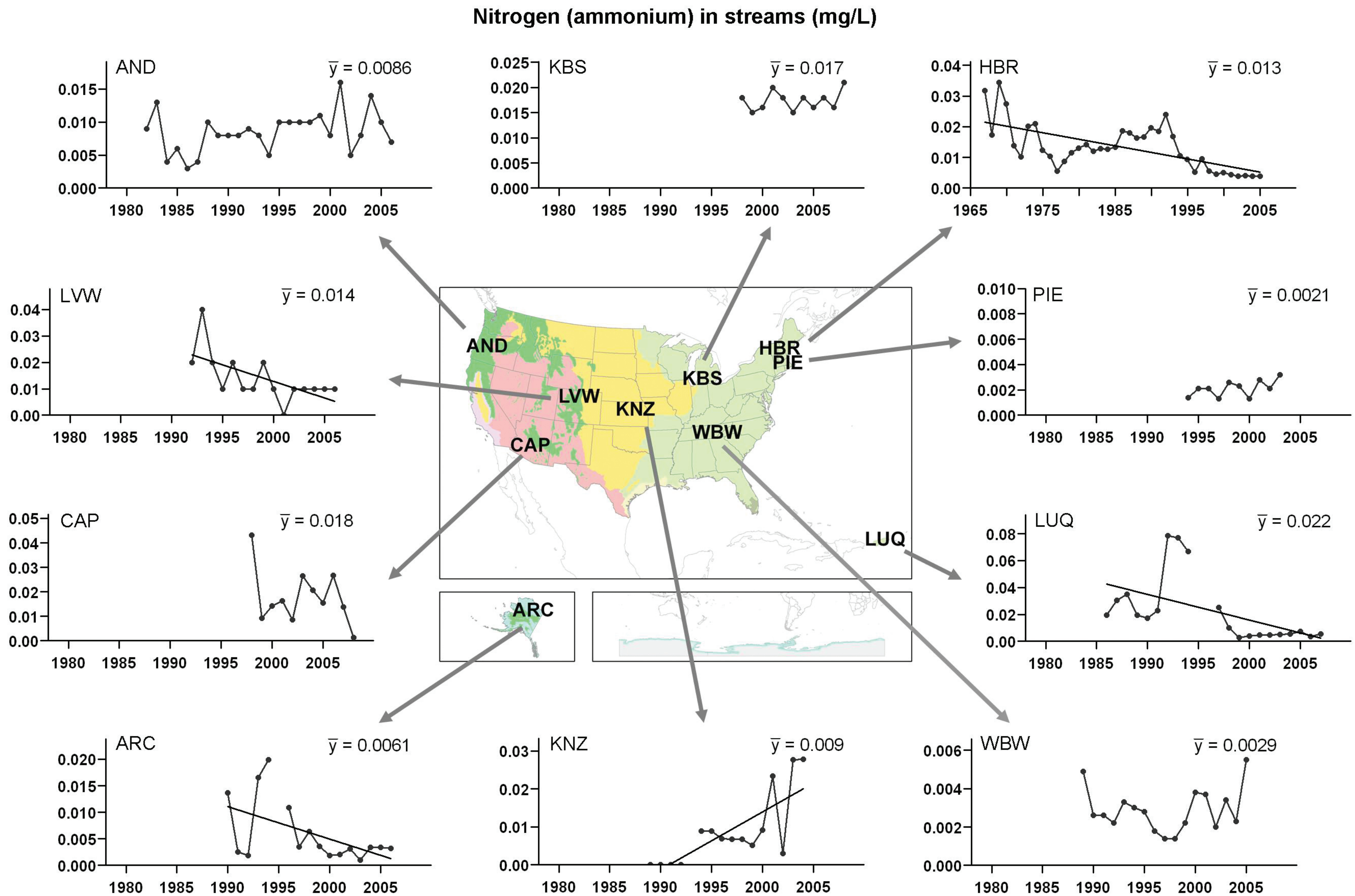


Figure 12-21. Concentration of nitrogen (ammonium, mg/L) in streams through time at ten sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Arctic (ARC) (-0.0006), Hubbard Brook Ecosystem Study (HBR) (-0.0004), Konza Prairie Biological Station (KNZ) (0.0015), Luquillo Experimental Forest (LUQ) (-0.0019), and Loch Vale Watershed (LVW) (-0.0013). Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

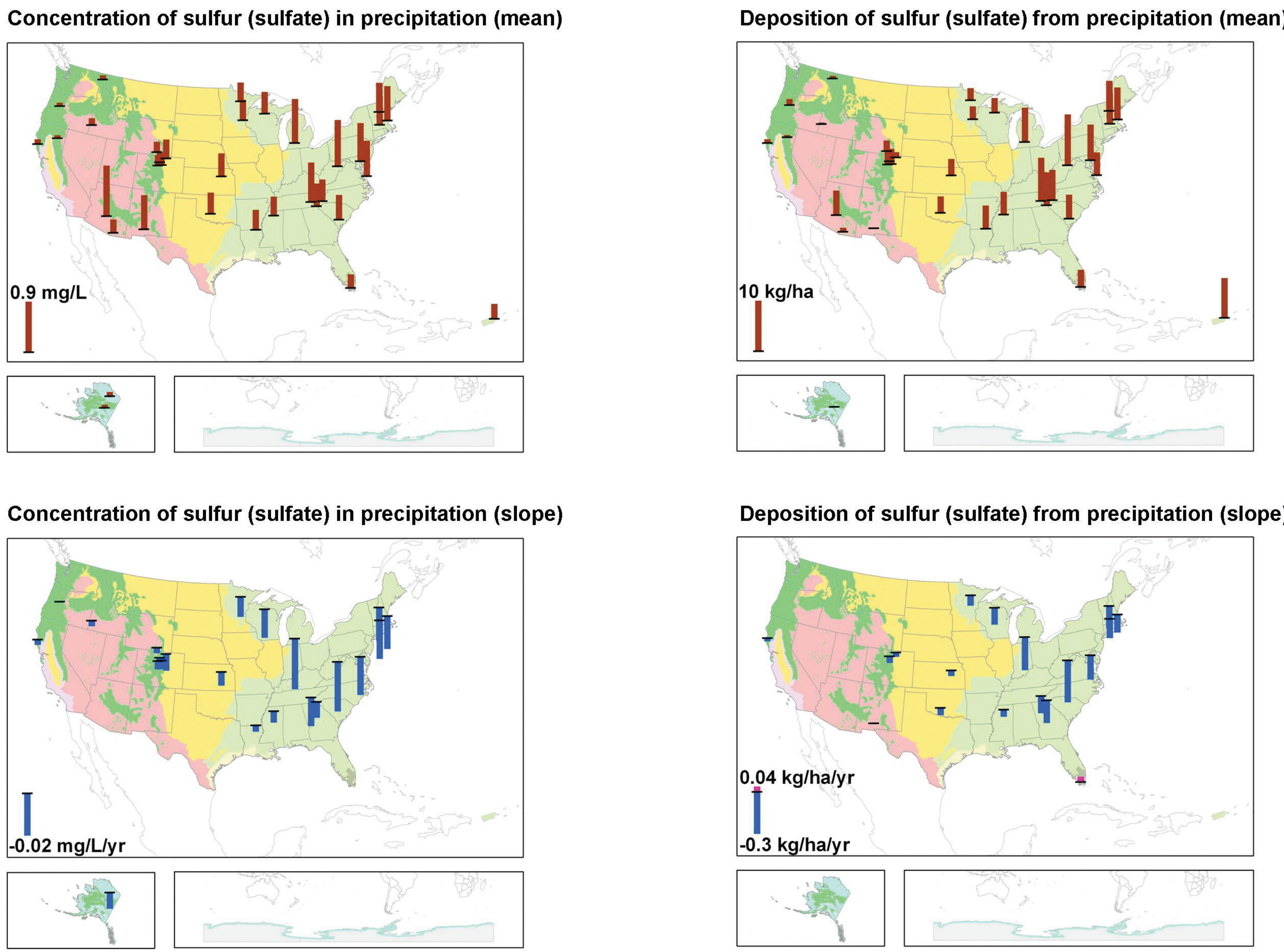


Figure 12-22. Continental patterns in sulfur (sulfate) from precipitation: concentration (volume-weighted concentration, mg/L) and wet deposition (kg/ha). Top panels: long-term averages; positive values are red and negative values are green. Bottom panels: slopes of significant regression lines ($p < 0.05$); positive values are pink and negative values are blue. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

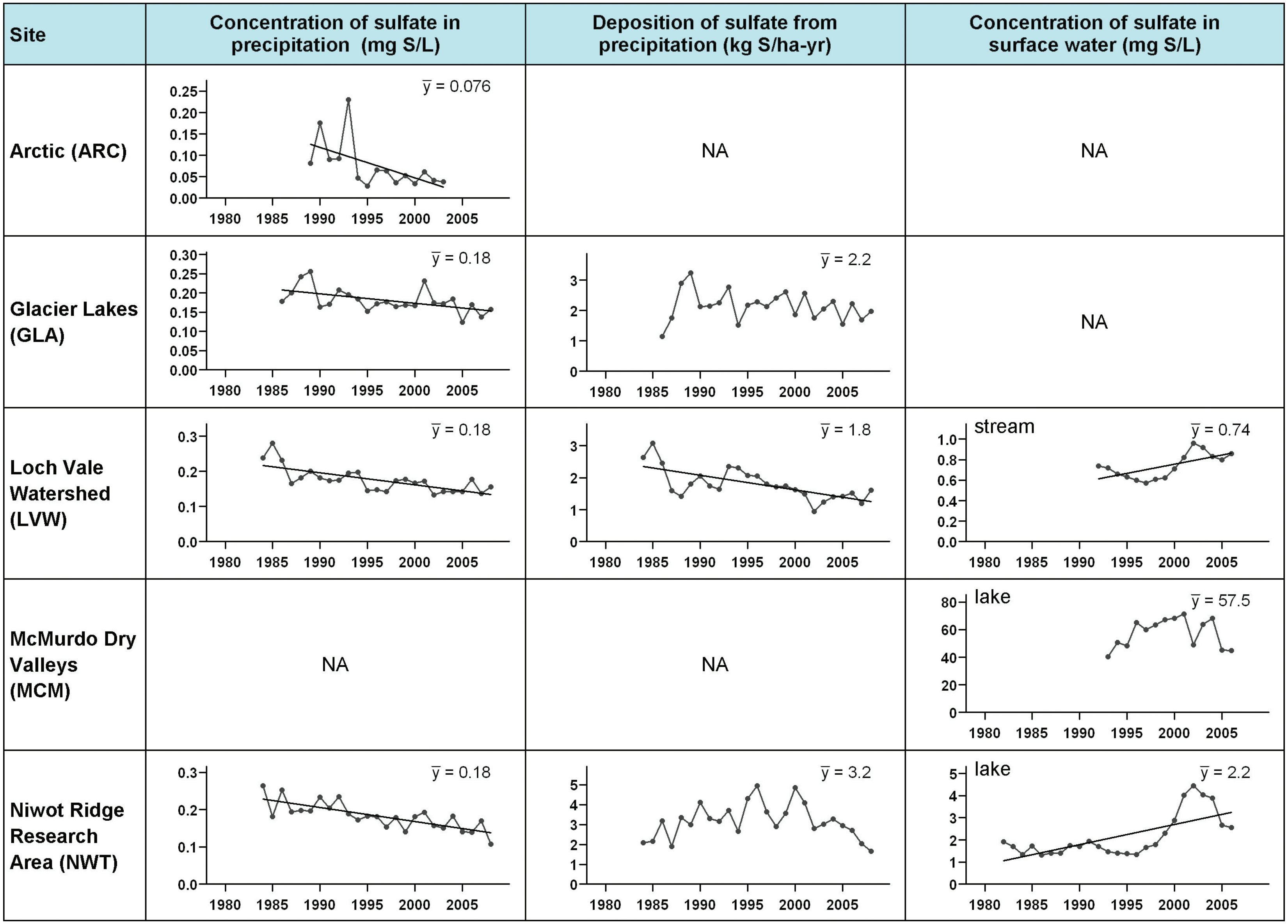


Figure 12-23. Trends for each alpine and arctic site: sulfate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Arctic (ARC): -0.007, NA, NA; Glacier Lakes (GLA): -0.002, NS, NA; Loch Vale Watershed (LVW): -0.003, -0.046, 0.018); McMurdo Dry Valleys (MCM): NA, NA, NS; and Niwot Ridge Research Area (NWT): -0.004, NS, 0.091. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

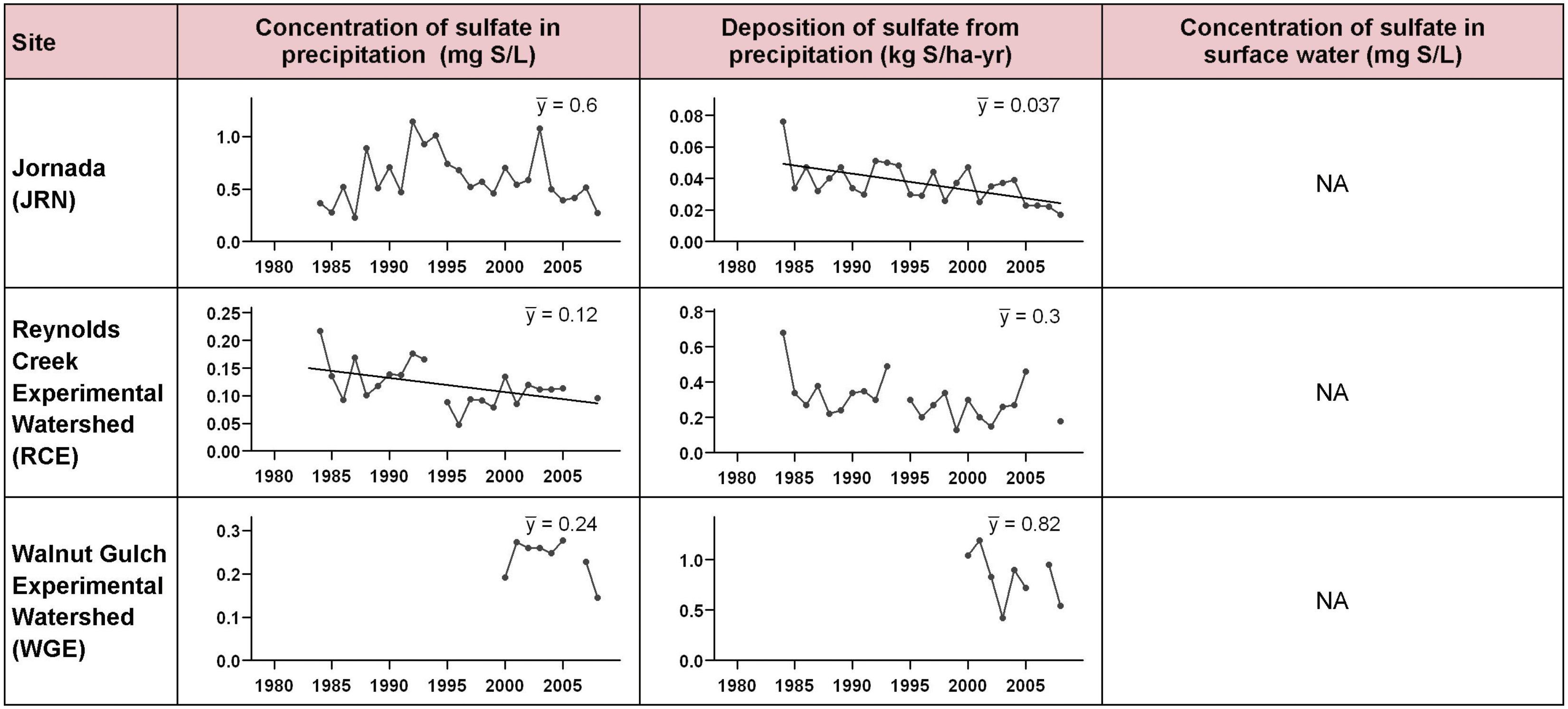


Figure 12-24. Trends for each aridland site: sulfate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Jornada (JRN): NS, -0.001, NA; Reynolds Creek Experimental Watershed (RCE): -0.003, NS, NA; and Walnut Gulch Experimental Watershed (WGE): NS, NS, NA. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

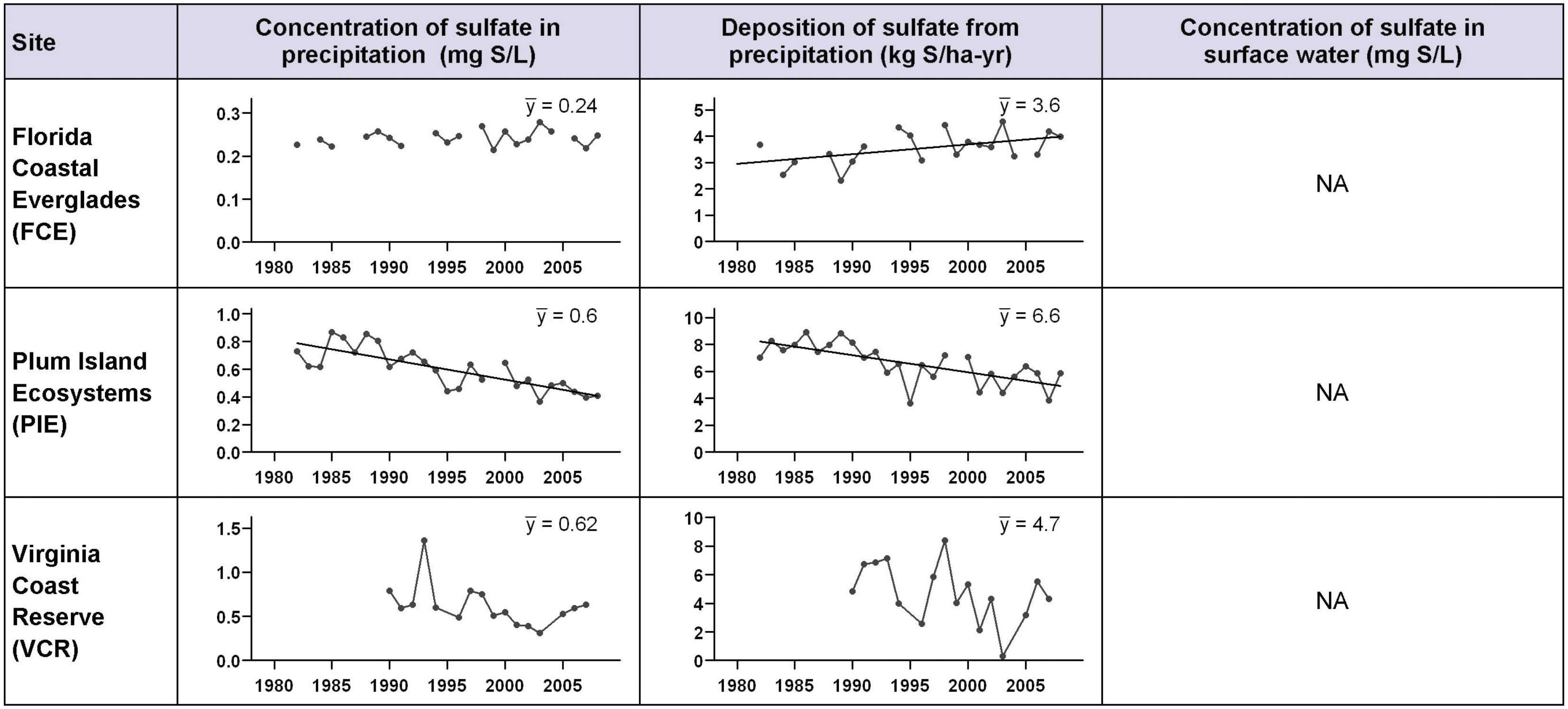


Figure 12-25. Trends for each coastal site: sulfate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Florida Coastal Everglades (FCE): NS, 0.037, NA; Plum Island Ecosystems (PIE): -0.015, -0.127, NA; and Virginia Coastal Reserve (VCR): NS, NS, NA. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

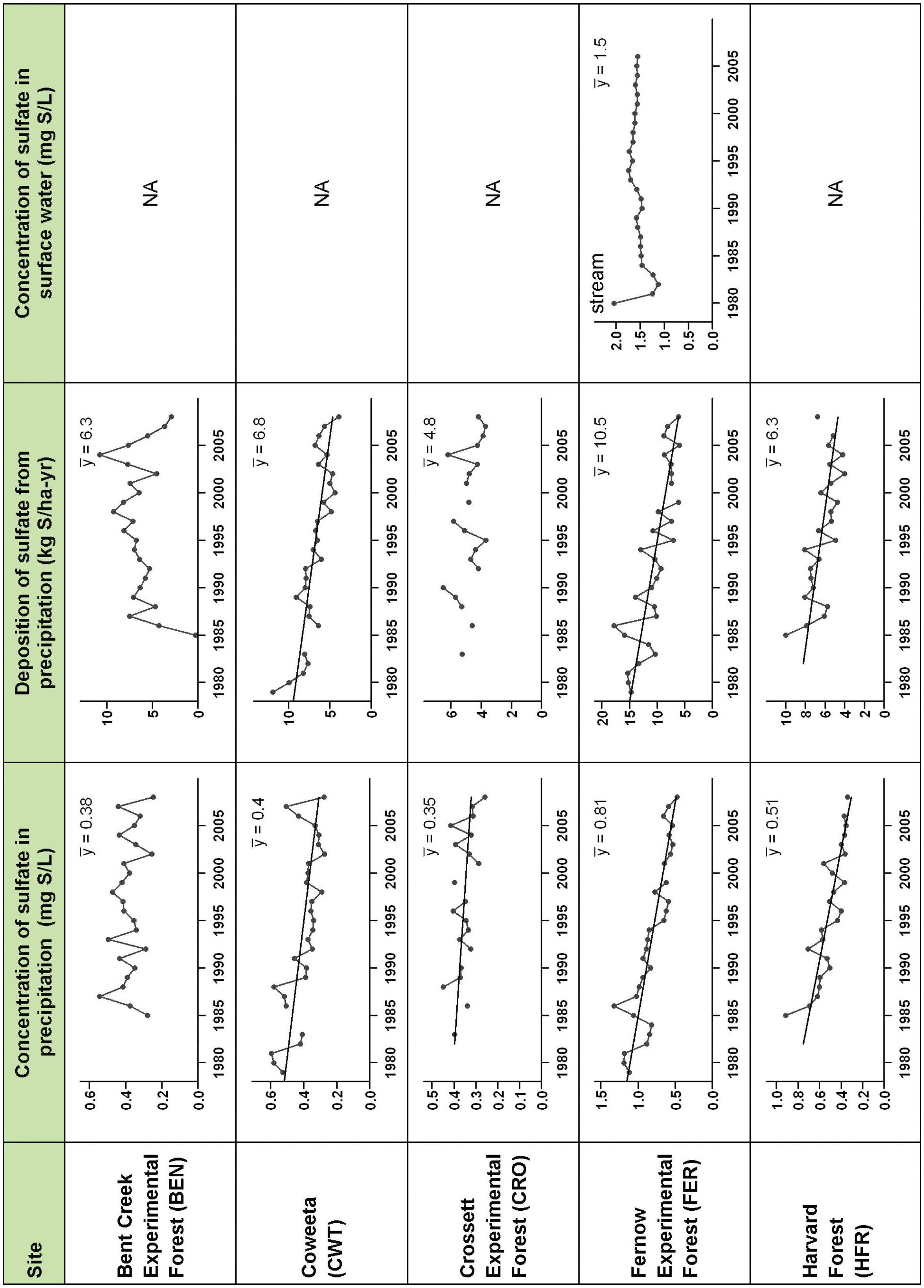


Figure 12-26 (eastern forest sites) continued next page.

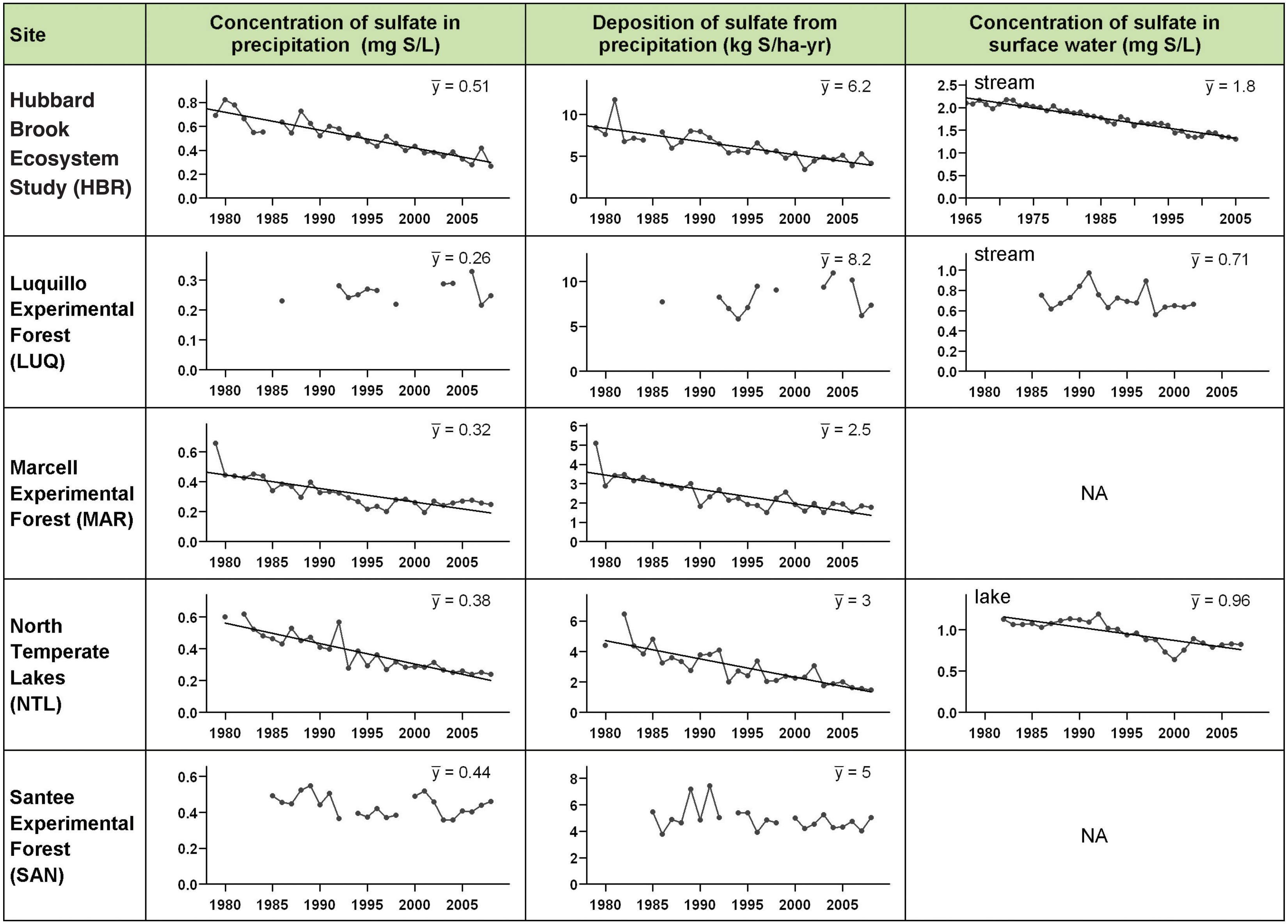


Figure 12-26 (eastern forest sites) continued next page.

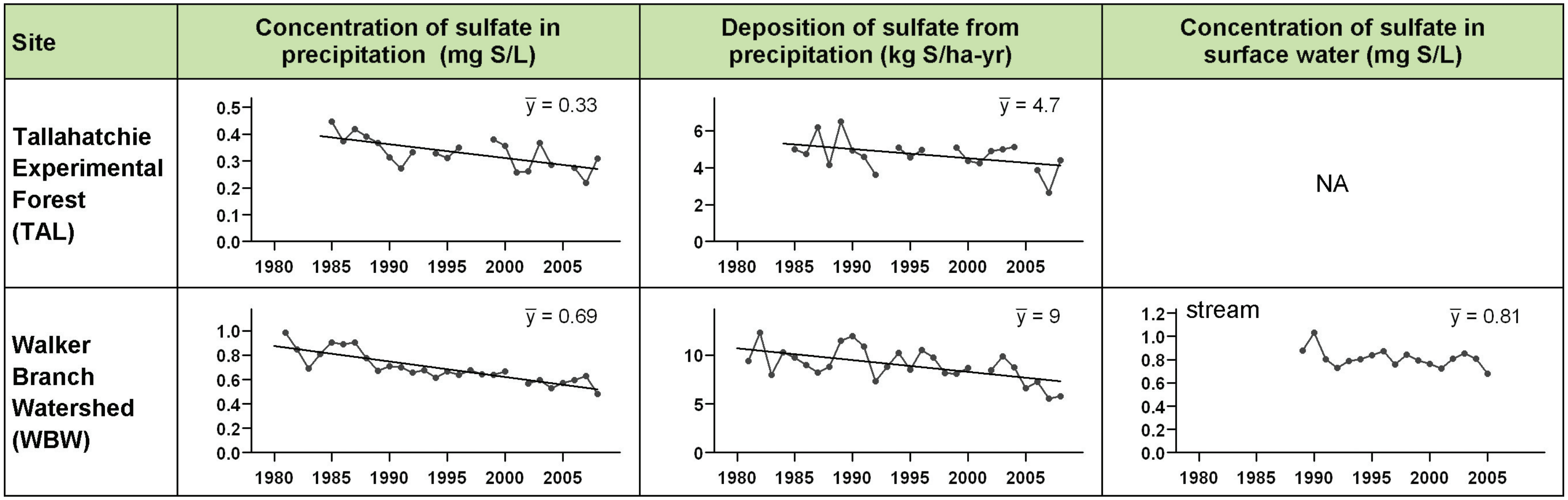


Figure 12-26. Trends for each eastern forest site: sulfate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Bent Creek Experimental Forest (BEN): NS, NS, NA; Crossett Experimental Forest (CRO): -0.003, NS, NA; Coweeta (CWT): -0.007, -0.158, NA; Fernow Experimental Forest (FER): -0.022, -0.293, NS; Hubbard Brook Ecosystem Study (HBR): -0.015, -0.157, -0.022; Harvard Forest (HFR): -0.017, -0.135, NA; Luquillo Experimental Forest (LUQ): NS, NS, NS; Marcell Experimental Forest (MAR): -0.009, -0.075, NA; North Temperate Lakes (NTL): -0.013, -0.120, -0.016; Santee Experimental Forest (SAN): NS, NS, NA; Tallahatchie Experimental Forest (TAL): -0.005, -0.050, NA; and Walker Branch Watershed (WBW): -0.013, -0.120, NS. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

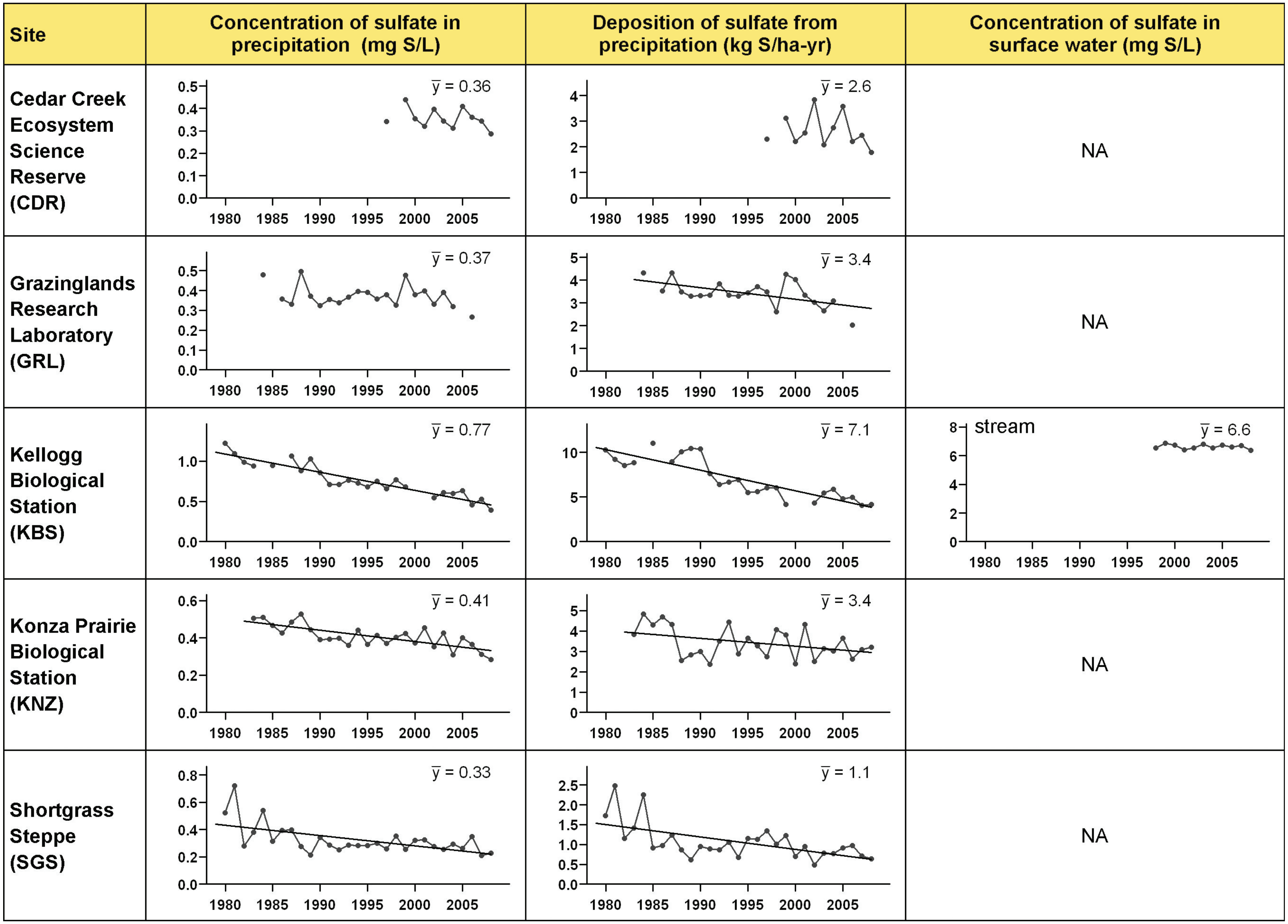


Figure 12-27. Trends for each temperate grassland and savanna site: sulfate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) Cedar Creek Ecosystem Science Reserve (CDR): NS, NS, NA; Grazinglands Research Laboratory (GRL): NS, -0.051, NA; Kellogg Biological Station (KBS): -0.023, -0.231, NS; Konza Prairie Biological Station (KNZ): -0.006, -0.039, NA; and Shortgrass Steppe (SGS): -0.007, -0.031, NA. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

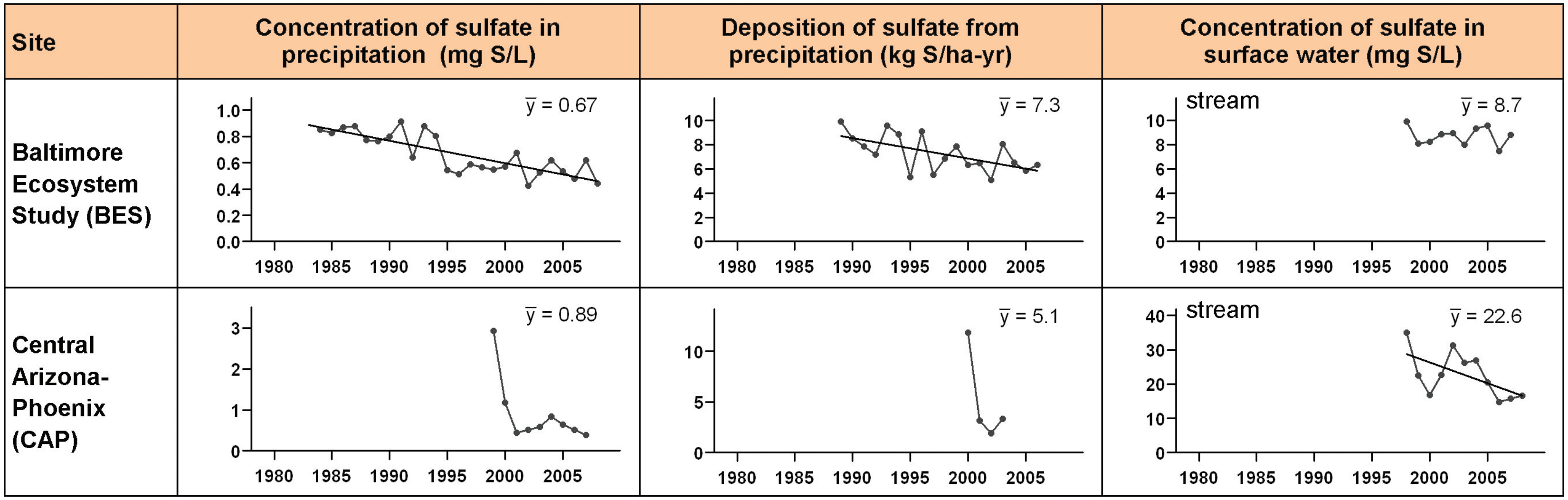


Figure 12-28. Trends for each urban site: sulfate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NS = not significant) Baltimore Ecosystem Study (BES): -0.017, -0.170, NS and Central Arizona-Phoenix (CAP): NS, NS, -1.215. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

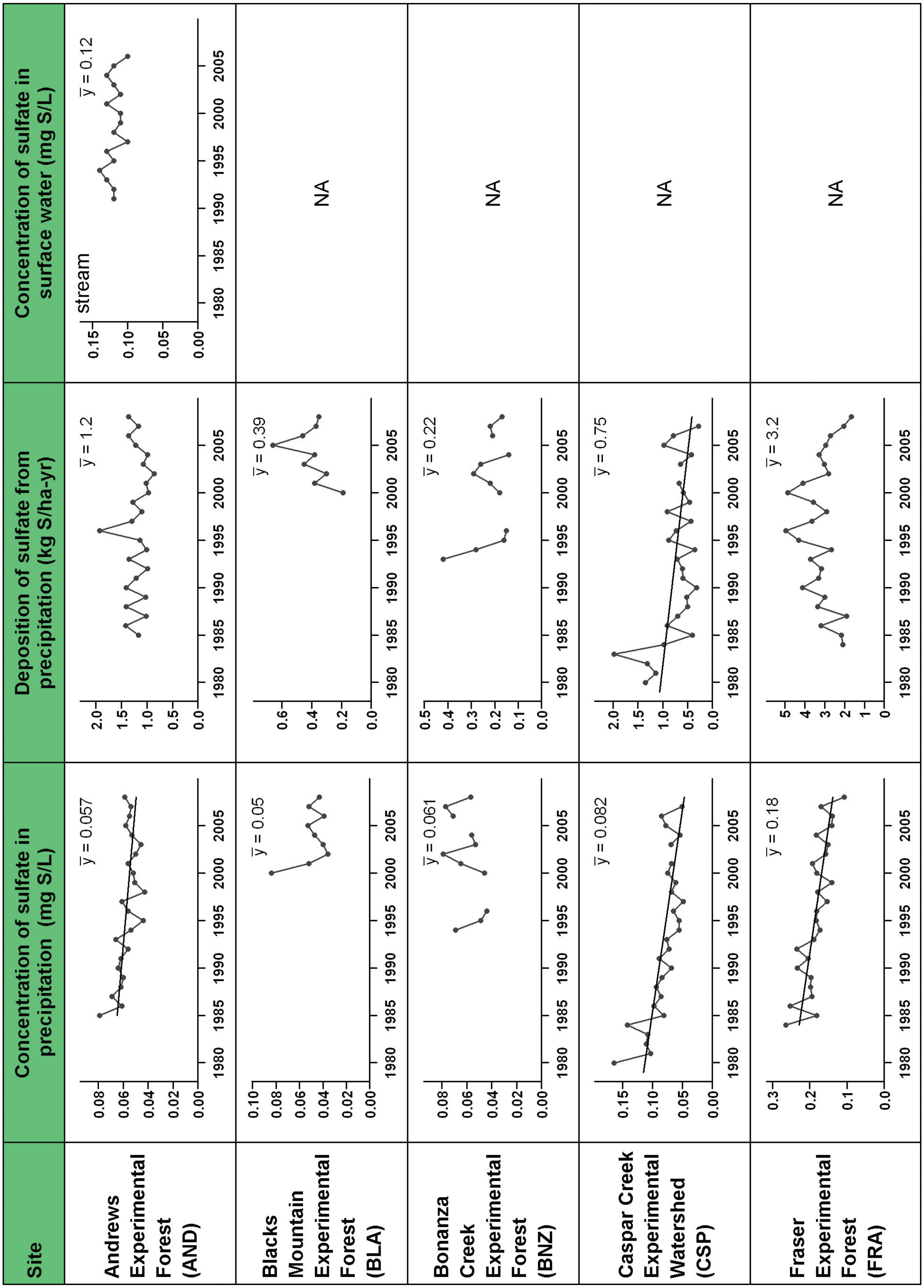


Figure 12-29 (western forest sites) continued next page.

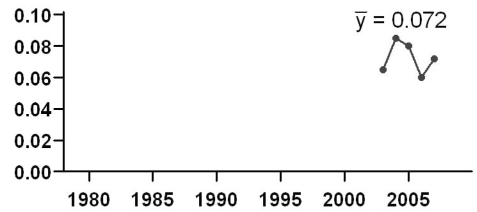
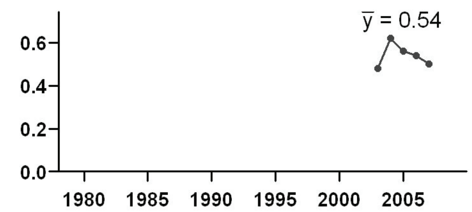
Site	Concentration of sulfate in precipitation (mg S/L)	Deposition of sulfate from precipitation (kg S/ha-yr)	Concentration of sulfate in surface water (mg S/L)
Priest River Experimental Forest (PRI)			NA

Figure 12-29. Trends for each western forest site: sulfate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, are (NA = not available, NS = not significant) H.J. Andrews Experimental Forest (AND): -0.001, NS, NS; Blacks Mountain Experimental Forest (BLA): NS, NS, NA; Bonanza Creek Experimental Forest (BNZ): NS, NS, NA; Caspar Creek Experimental Watershed (CSP): -0.002, -0.022, NA; Fraser Experimental Forest (FRA): -0.004, NS, NA; and Priest River Experimental Forest (PRI): NS, NS, NA. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

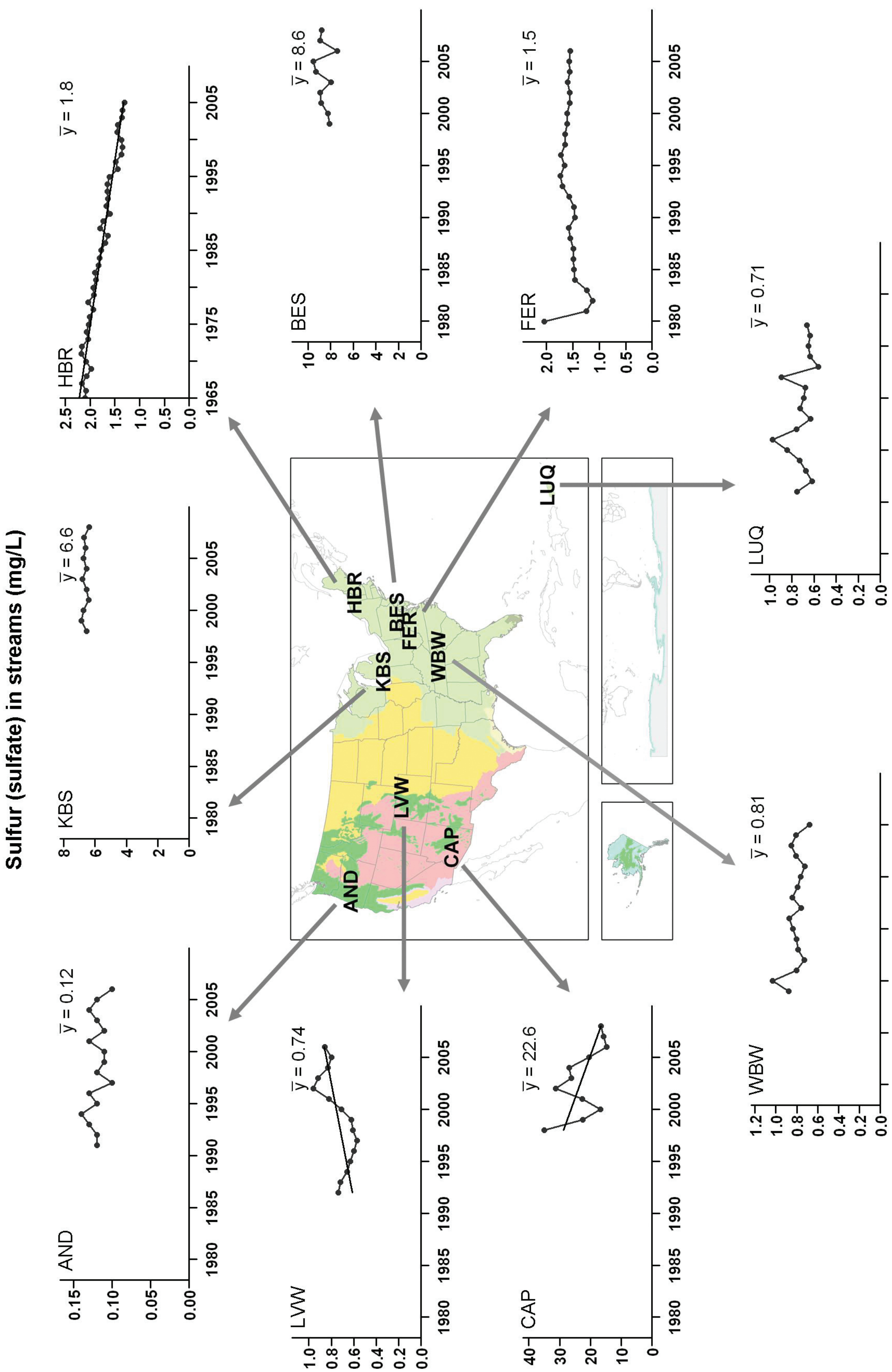


Figure 12-30. Concentration of sulfur (sulfate, mg/L) in streams through time at nine sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Central Arizona-Phoenix (CAP) (-1.22), Hubbard Brook Ecosystem Study (HBR) (-0.02), and Loch Vale Watershed (LVW) (0.02). Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.eco-trends.info.

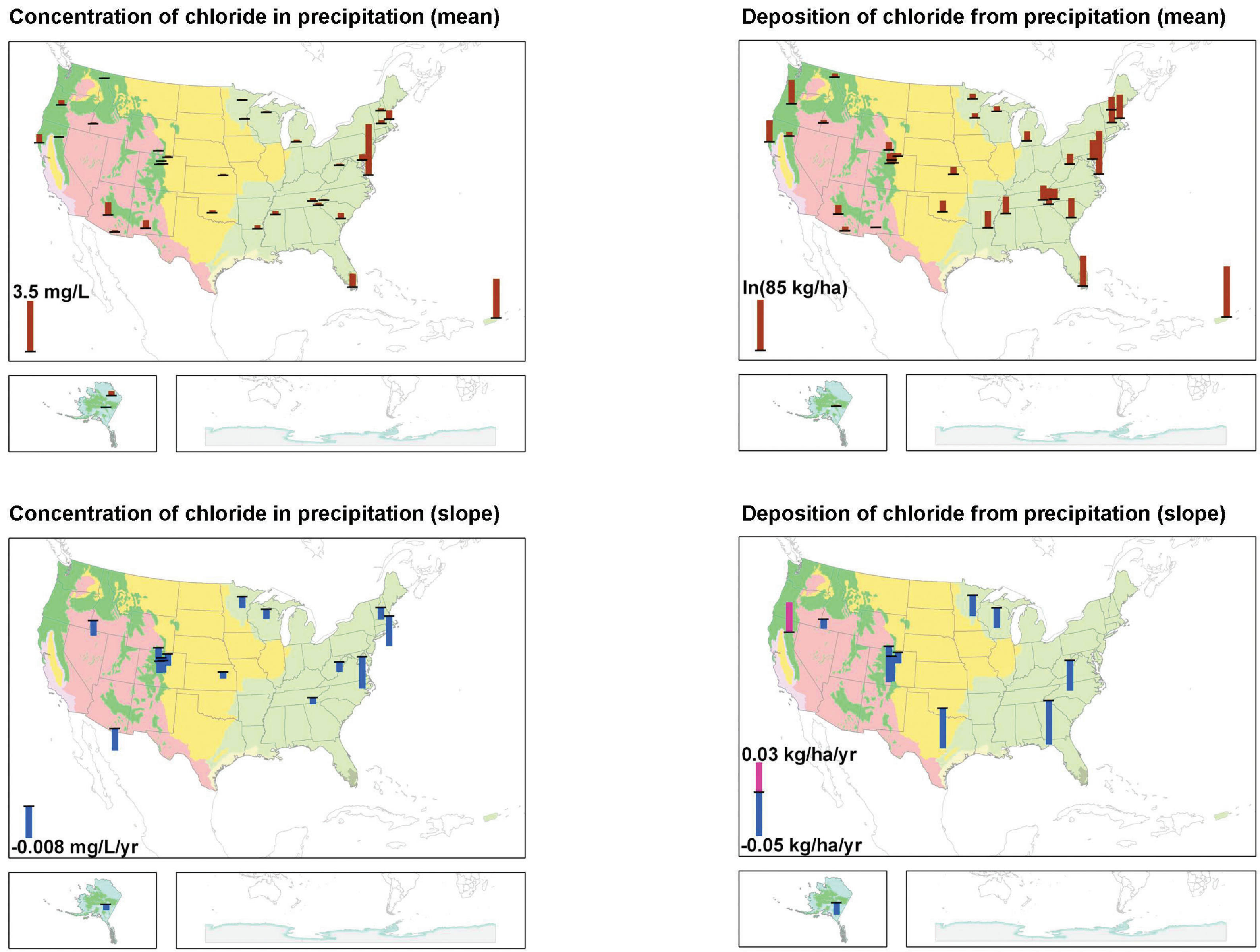


Figure 12-31. Continental patterns in chloride from precipitation: concentration (volume-weighted concentration, mg/L) and wet deposition (kg/ha). Top panels: long-term averages; positive values are red and negative values are green. Bottom panels: slopes of significant regression lines ($p < 0.05$); positive values are pink and negative values are blue. For the means of deposition from precipitation, the bar height is the ln-transformed value [ln(1+mean)]. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/.
Synthesized data from http://www.ecotrends.info.

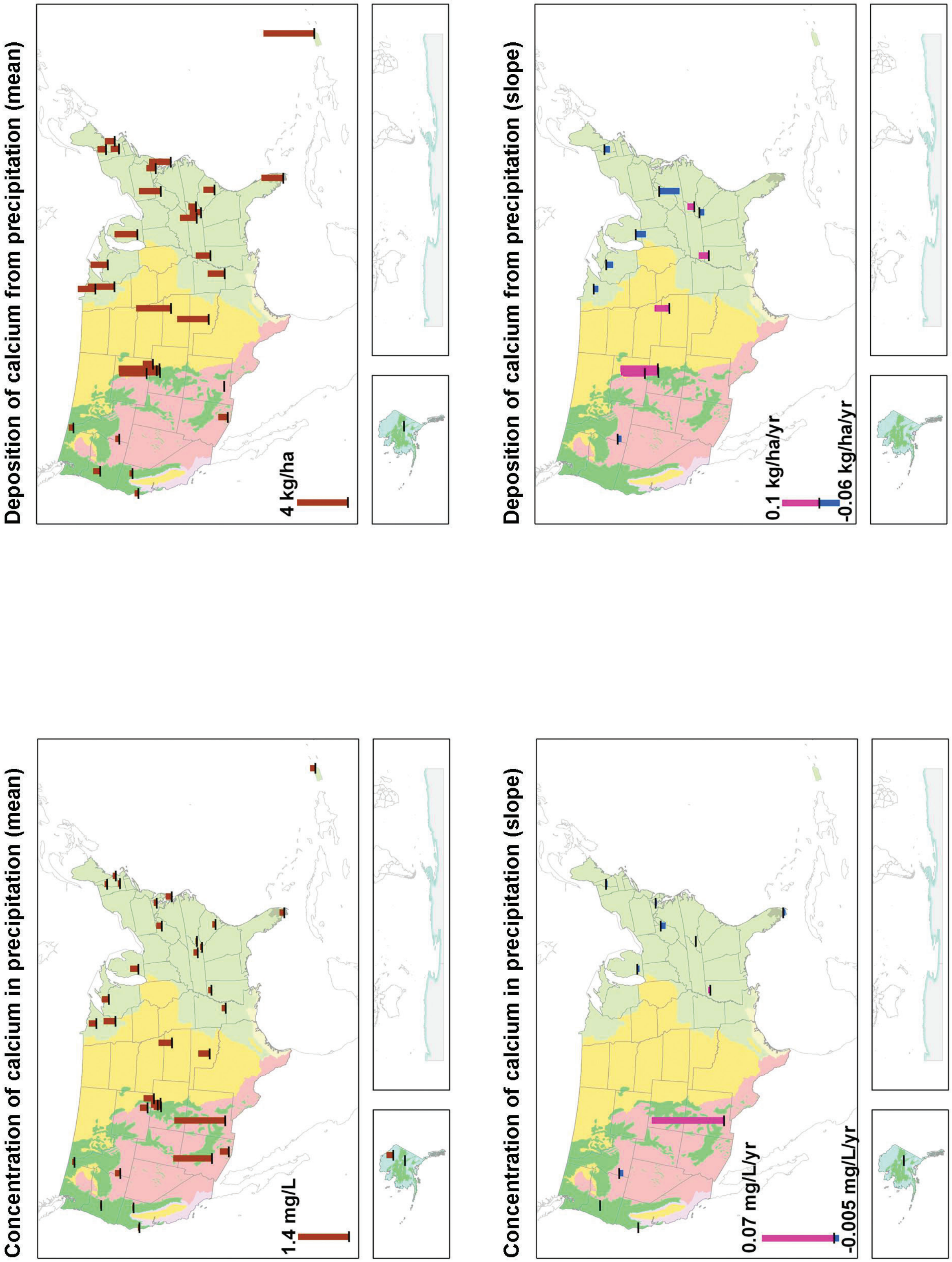


Figure 12-32. Continental patterns in calcium from precipitation: concentration (volume-weighted concentration, mg/L) and wet deposition (kg/ha). Top panels: long-term averages; positive values are red and negative values are green. Bottom panels: slopes of significant regression lines ($p < 0.05$); positive values are pink and negative values are blue. Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

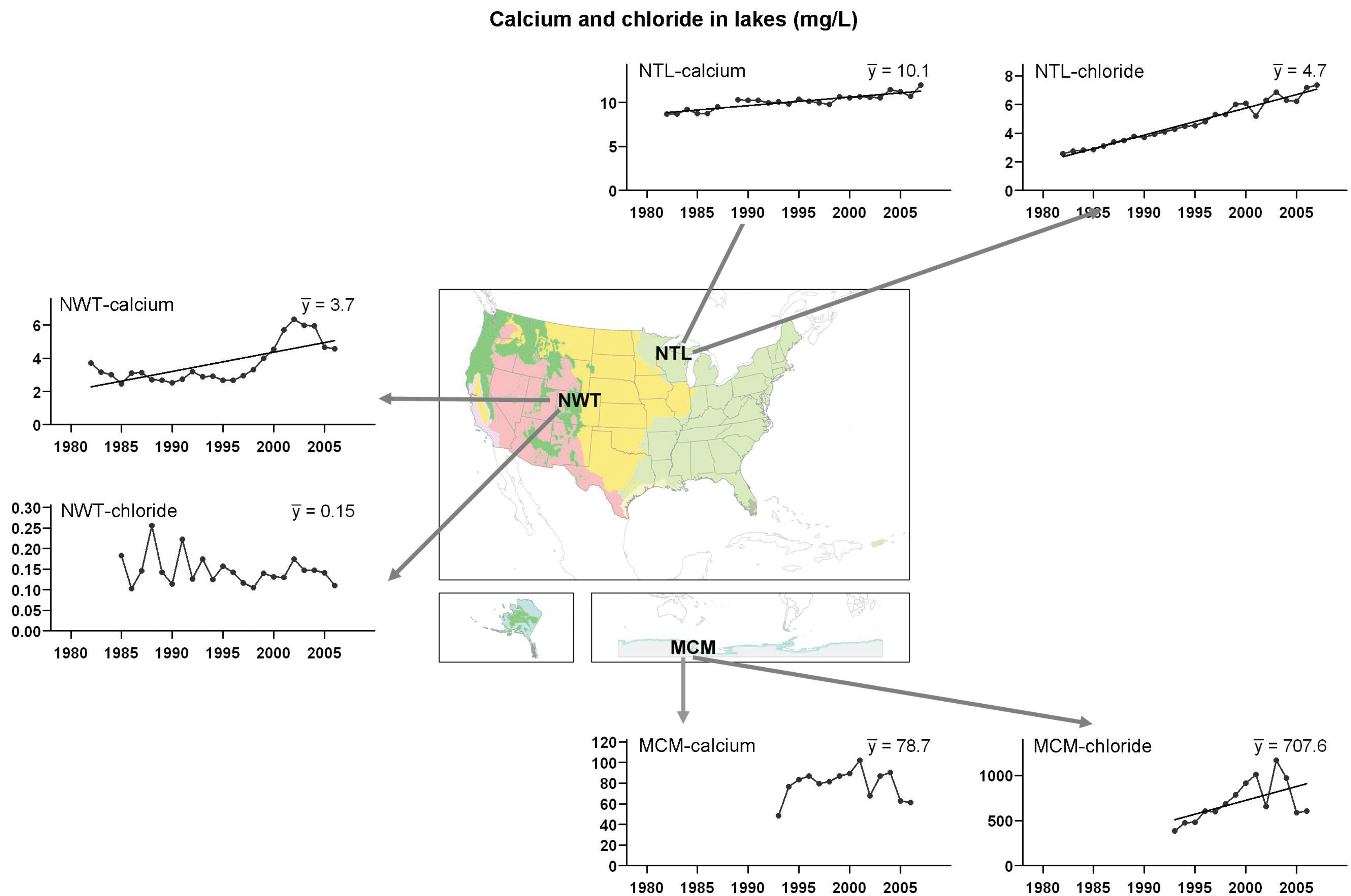


Figure 12-33. Concentrations of calcium and chloride (mg/L) in lakes through time at three sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are McMurdo Dry Valleys (MCM) (30.38 chloride), North Temperate Lakes (NTL) (0.10 calcium, 0.19 chloride), and Niwot Ridge Research Area (NWT) (0.12 calcium). Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

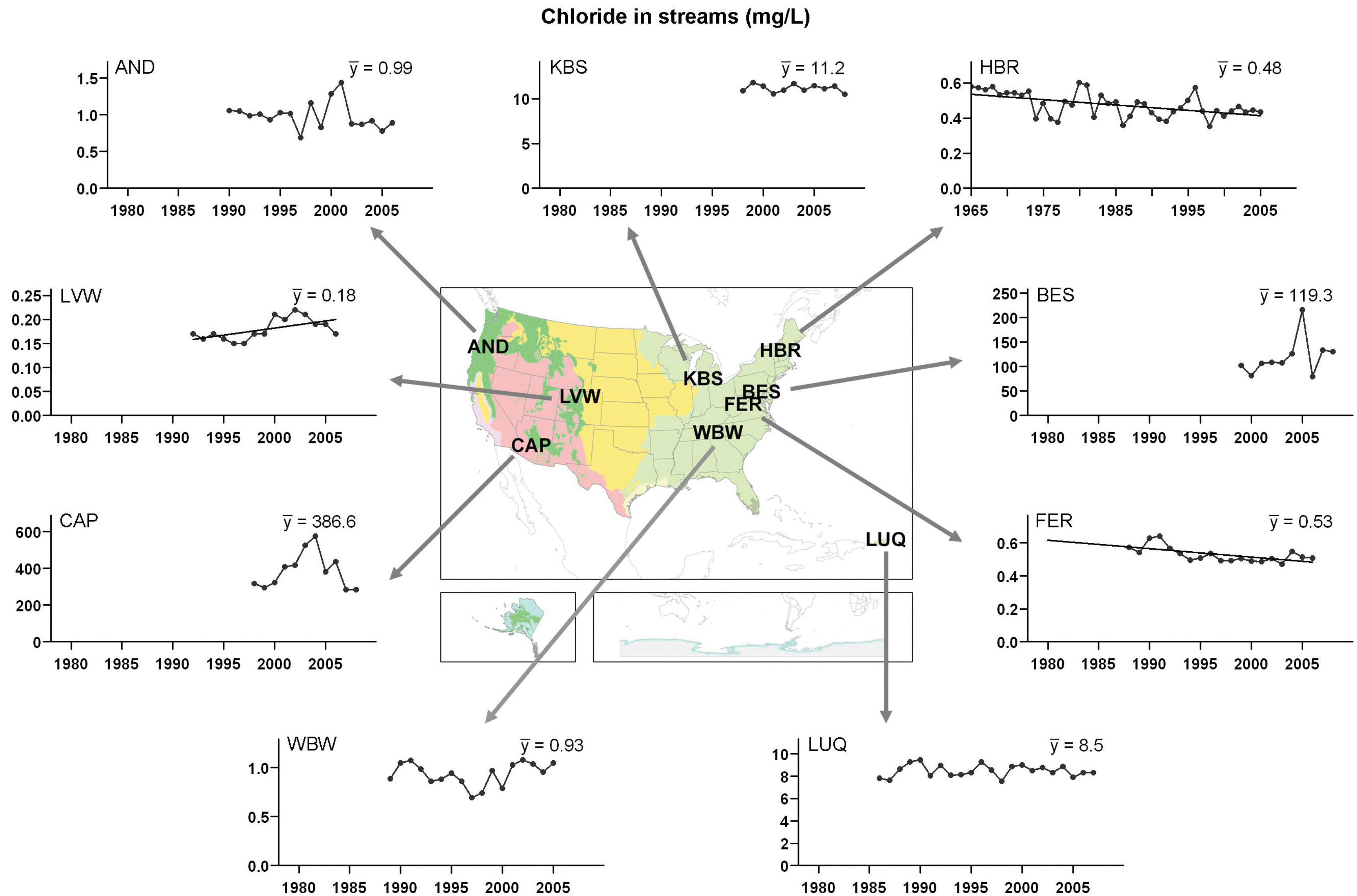


Figure 12-34. Concentration of chloride (mg/L) in streams through time at nine sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Fernow Experimental Forest (FER) (-0.005), Hubbard Brook Ecosystem Study (HBR) (-0.003), and Loch Vale Watershed (LVW) (0.003). Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

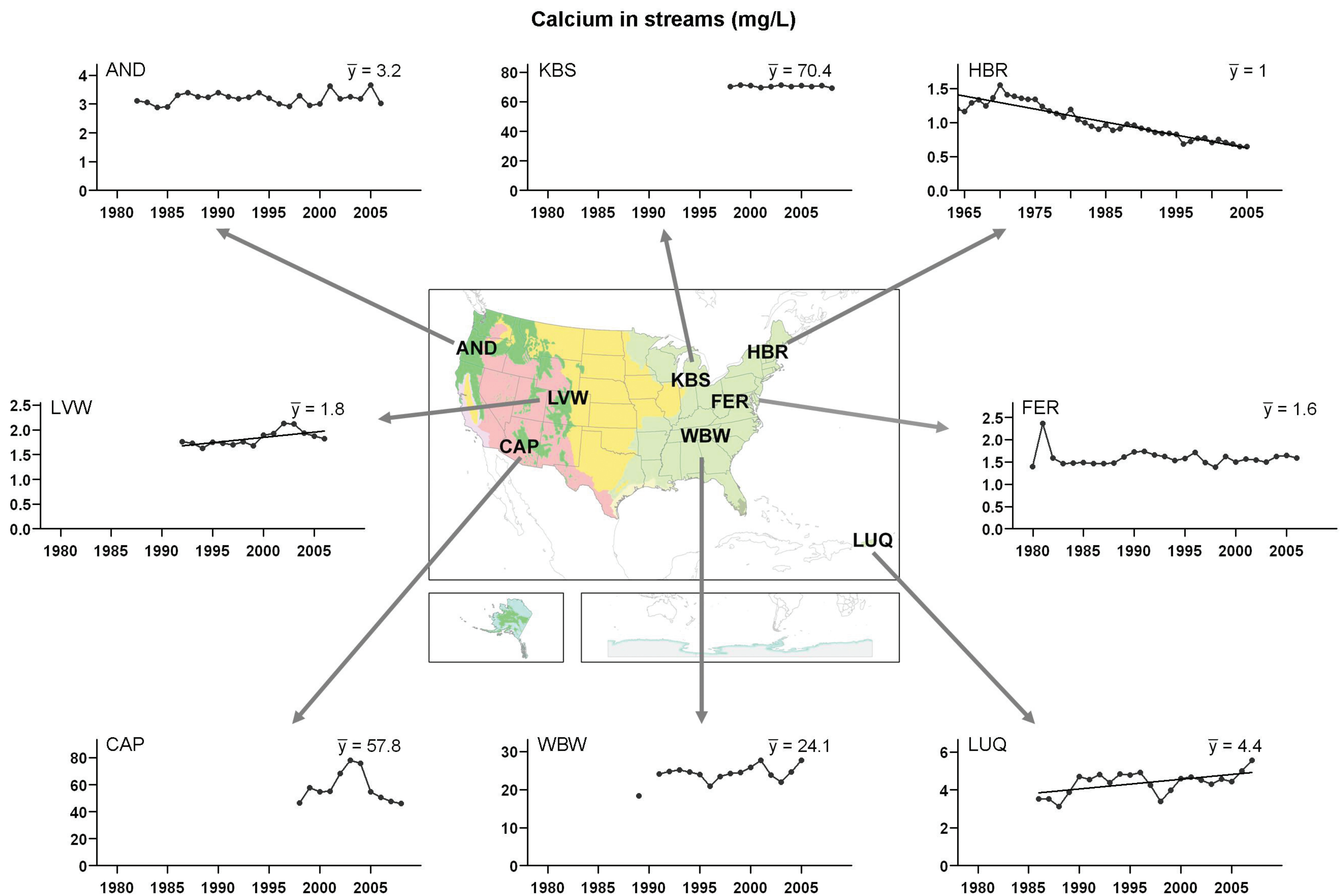


Figure 12-35. Concentration of calcium (mg/L) in streams through time at eight sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Hubbard Brook Ecosystem Study (HBR) (-0.02), Luquillo Experimental Forest (LUQ) (0.05), and Loch Vale Watershed (LVW) (0.02). Original data from Internet home pages (see table 1-1) and http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

Chapter 13

Long-Term Trends in Human Demography and Economy Across Sites

In this chapter, we first describe the methods used to obtain data on human populations and the variables used in this report. We then show graphs of human population and economic data by county for each site, as well as summary maps at the continental scale. Scientific hypotheses and the rationale for comparing these data can be found in chapter 8.

Methods of Obtaining Data and Selection of Variables

In the United States, the Census Bureau and the USDA National Agricultural Statistics Service are the original sources for many long-term population and economic data. These data are available online directly (www.census.gov) or through separate initiatives, such as the Inter-University Consortium for Political and Social Research (http://www.icpsr.umich.edu/icpsrweb/ICPSR/). Since 1790, the Census Bureau has collected information every 10 years on the population and economic characteristics of the country. Sites east of the Appalachian Mountains typically have census data from 1790; most areas west of the Rocky Mountains have data starting after 1860, and Alaska has data since 1970. Because of funding constraints, we focused on collecting key population and economic variables for counties selected to represent each site. Census data are not available for sites in Antarctica or French Polynesia; thus a total of 47 sites are included in the current analysis (table 13-1). Scientists at each site provided the names of counties associated with their site that, in most cases, went beyond the boundaries of the research site per se.

We tabulated census data for three population variables for each county in each year of the census: total population, the percentage of the population living in urban areas, and the density of people in the county (number of people per km^2). Because counties differ in their area covered, the total population size of a county in a year was divided by the county area to obtain an average density value for that year. We also tabulated economic variables for each county—percentage of the population employed by one of four economic sectors: commercial industries, farming, manufacturing, and service industries. Data for these variables are also available on the EcoTrends website (http://www.ecotrends.info) and on an associated website (http://coweeta.ecology.uga.edu/trends/).

Graphs Showing Long-Term Trends

We display the long-term data in two ways to show change through time across a range of spatial scales for each variable. First, we provide a summary of the data at the continental scale using maps that show either the change in total population for four time periods (1800 to 1850, 1850 to 1900, 1900 to 1950, and 1950 to 2000) or the percentage of the population that was urban at the end of each of the four time periods (1850, 1900, 1950, 2000). Following the continental maps, we show site-scale data through time using five panels: (1) a map showing the location of the counties associated with the site, (2) total population by county, (3) percentage of the population that was urban in each county, (4) population density by county, and (5) percentage of the population in each economic sector in the focal county where the site resides. The site graphs are organized by ecosystem type to allow comparisons of sites in the same type. For the 2000 census, total population, population density, urban percentage of the population, and percentage of the population in each economic sector in the focal county can be found in appendix 15.

Summary

Several trends are noticeable at the continental scale. The settlement of the country progressed from the east coast and then jumped to the west coast by 1900, and then to the interior between 1900 and 1950 (figure 13-1). The Midwest lost population between 1950 and 2000. Most areas of the country had a high percentage of urban population by 1950 (figure 13-2). Urbanization continued for most of the country until 2000 with the Northeast, Appalachian Mountains, and northern Wisconsin providing notable exceptions.

Table 13-1. Counties selected to represent each site used in the analysis of population and economic data
(The focal county based on the location of the research site is in bold. Additional counties for some sites are available on the EcoTrends website at http://www.ecotrends.info.)

Site code	State	Counties
AND	OR	Benton, Deschutes, Douglas, **Lane**, Linn
ARC	AK	**North Slope Borough**
BEN	NC	**Buncombe**
BES	MD	Anne Arundel, **Baltimore City**, Baltimore County, Carroll, Howard
BLA	CA	**Lassen**
BNZ	AK	**Fairbanks North Star Borough**
CAP	AZ	**Maricopa**, Pinal
CCE	CA	Los Angeles, Orange, **San Diego,** Ventura
CDR	MN	**Anoka**, Hennepin, Isanti
CHE	OR	Lincoln, **Tillamook**
CRO	AR	**Ashley**
CSP	CA	**Mendocino**
CWT	GA	Rabun, Towns
	NC	Clay, Jackson, **Macon**
EOA	OR	**Harney**
FCE	FL	Broward, Collier, **Miami-Dade**, Monroe, Palm Beach
FER	WV	**Tucker**
FRA	CO	**Grand**
FTK	MT	**Custer**
GCE	GA	Bryan, Camden, Glynn, Liberty, **McIntosh**
GLA	WY	**Albany**, Carbon
GRL	OK	Caddo, Comanche, **Grady**
GSW	TX	**Bell**, Falls, McLennan
HAR	MS	**Harrison**, Stone
HBR	NH	**Grafton**
HFR	MA	Berkshire, Franklin, Hampden, Hampshire, **Worcester**
JRN	NM	**Doña Ana**
KBS	MI	Allegan, Barry, Calhoun, Eaton, **Kalamazoo**
KNZ	KS	Geary, Morris, Pottawatomie, **Riley**, Wabaunsee
LUQ	PR	Ceiba, Fajardo, Luquillo, Naguabo, **Rio Grande**

Table 13-1. Counties selected to represent each site used in the analysis of population and economic data—*Continued*

Site code	State	Counties
LVW	CO	Boulder, Grand, **Larimer**
MAR	MN	**Itasca**
MCM[1]		No data
MCR[2]		No data
NTL	WI	**Dane**, Oneida, Vilas
NWT	CO	**Boulder**
PAL[1]		No data
PIE	MA	**Essex**, Middlesex
PRI	ID	**Bonner**
RCE	ID	**Owyhee**
SAN	SC	**Berkeley**
SBC	CA	**Santa Barbara**
SEV	NM	Bernalillo, Sandoval, **Socorro**, Valencia
SGS	CO	**Weld**
	WY	Laramie
SPR	OK	**Woodward**
SRE	AZ	**Pima**, Santa Cruz
TAL	MS	**Lafayette**
VCR	VA	Accomack, **Northampton**
WBW	TN	Anderson, Loudon, **Roane**
WGE	AZ	Pima, **Santa Cruz**
WIN	WA	**Skamania**

[1] MCM and PAL are located in Antarctica.

[2] MCR is located at the island of Moorea in French Polynesia.

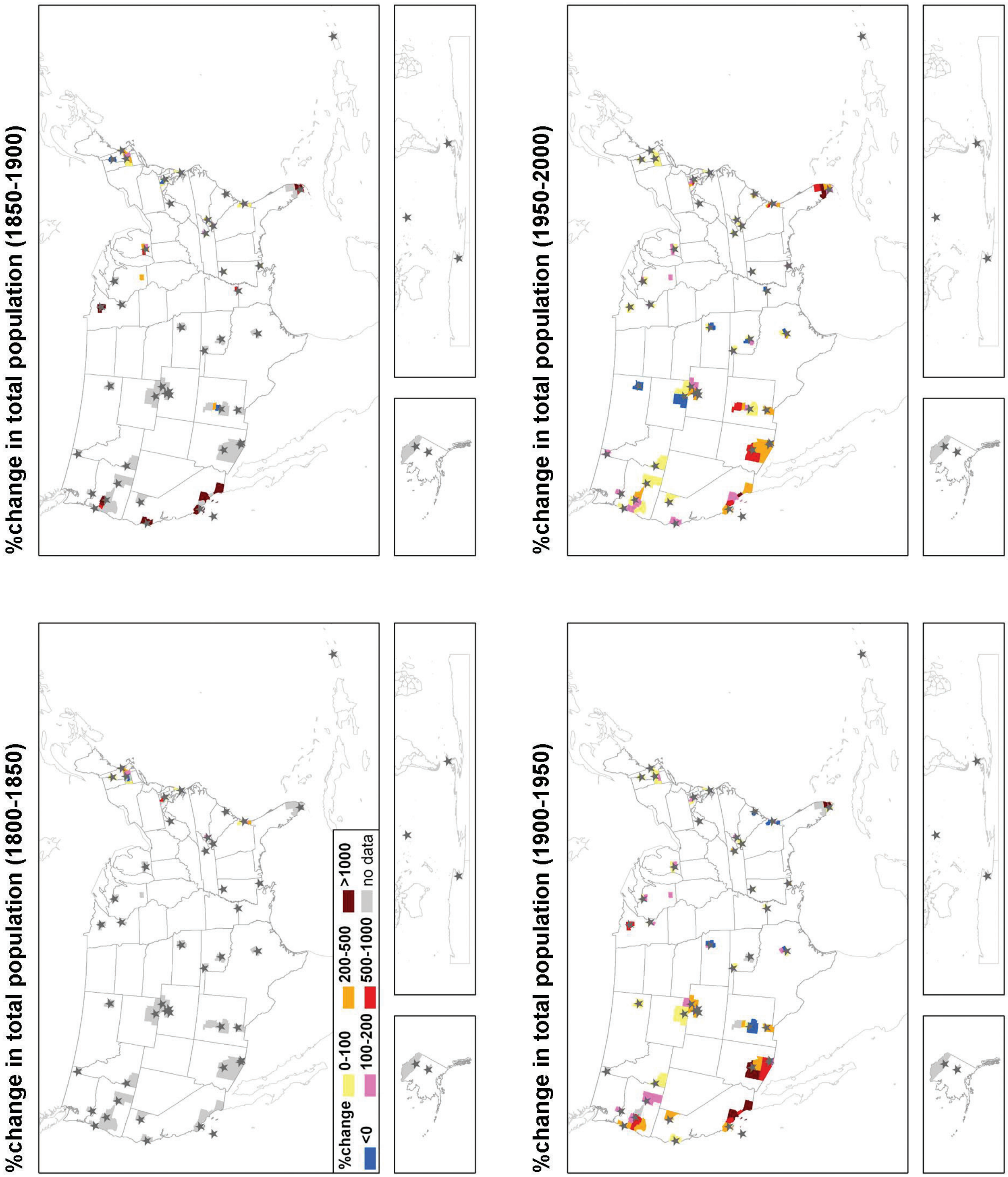


Figure 13-1. Continental pattern of percentage change in total population over time by county calculated as [(year 2 - year 1)/year 1] × 100 for 4 time periods: 1800-1850, 1850-1900, 1900-1950, and 1950-2000. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

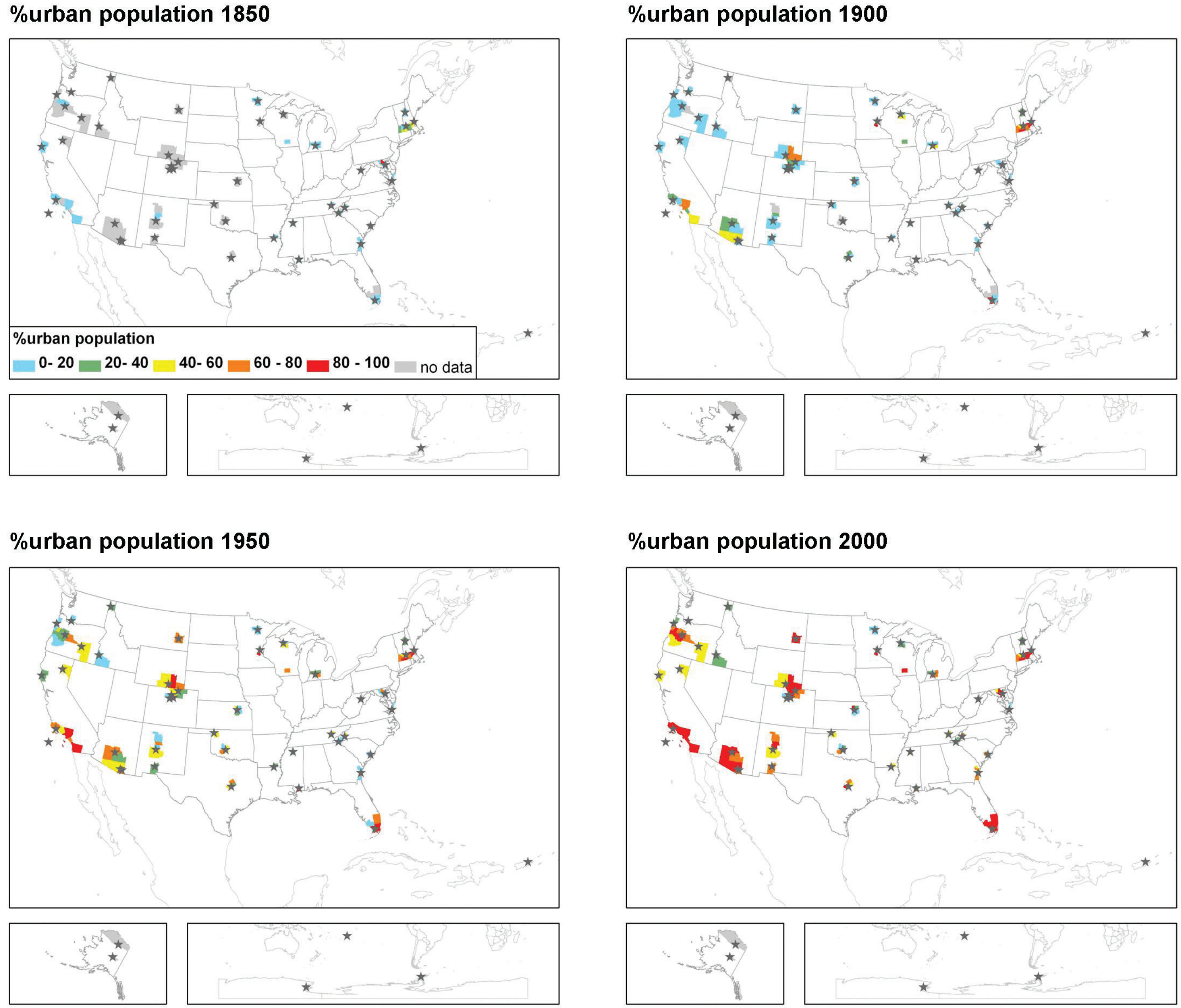


Figure 13-2. Continental pattern of percentage urban population by county over time calculated as (number of people living in urban areas / total number of people) × 100 in 1850, 1900, 1950, and 2000. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

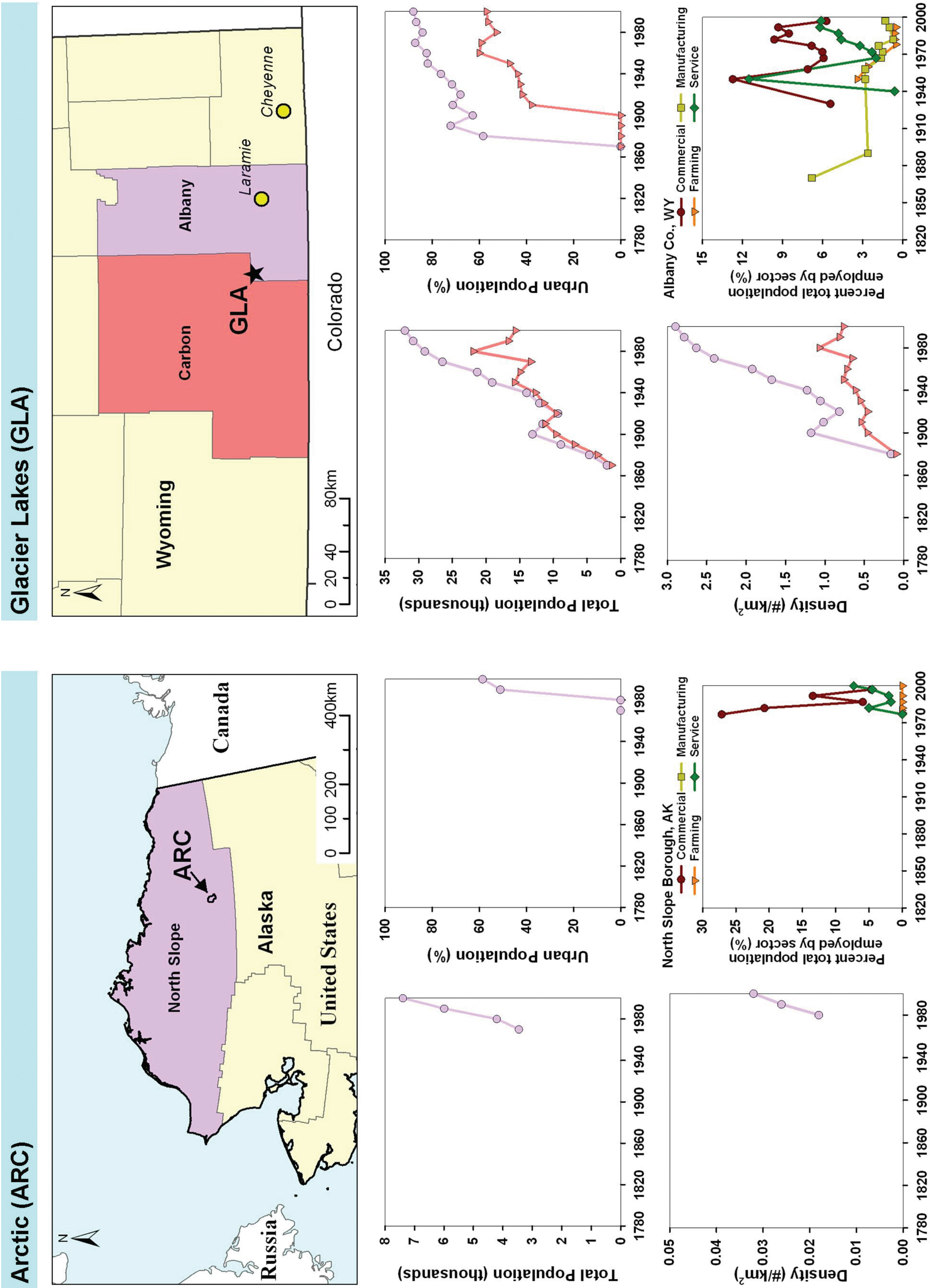


Figure 13-3 (Alpine and Arctic sites) continued next page.

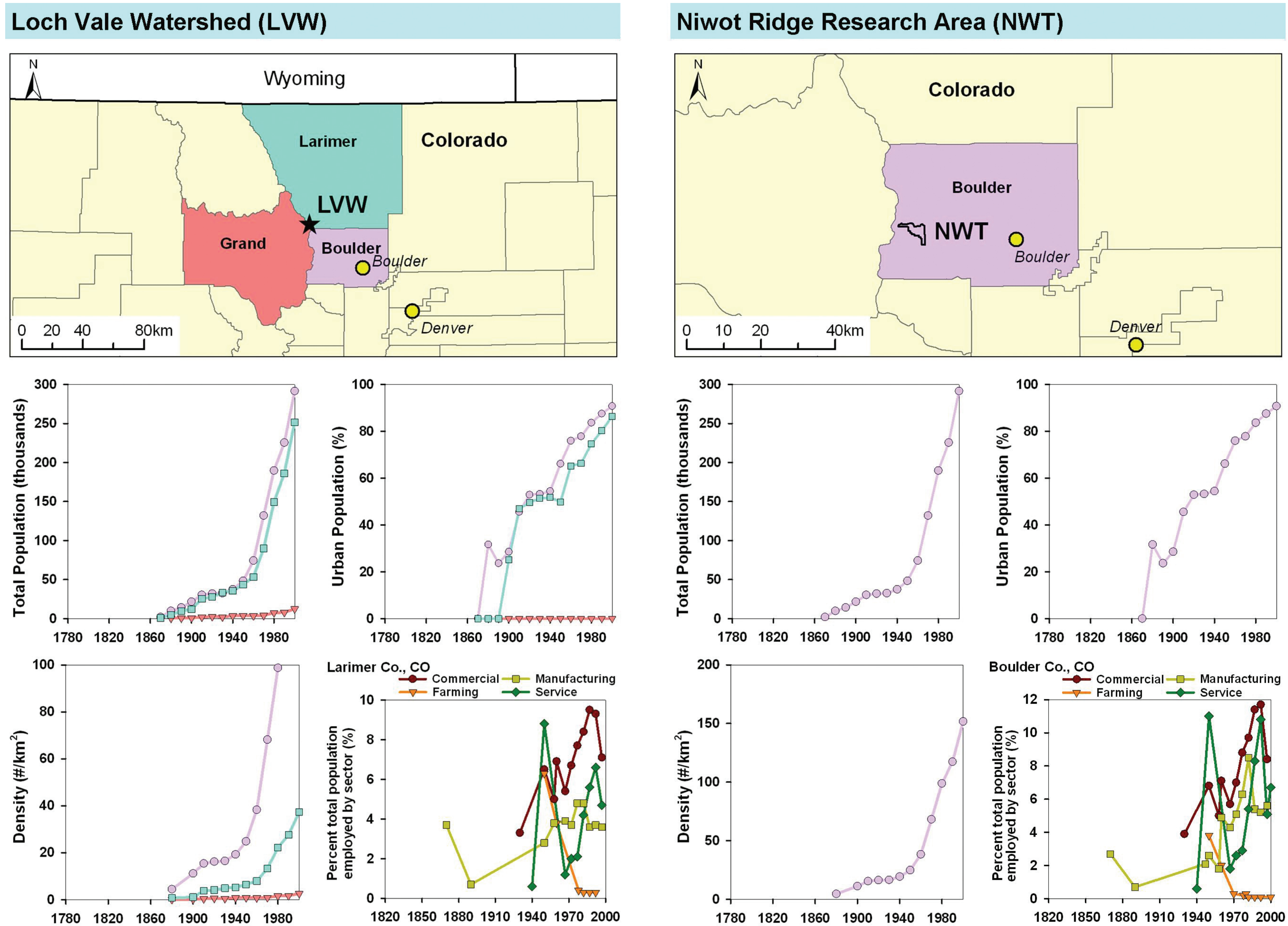


Figure 13-3. Trends for each alpine and arctic site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and percentage of total population employed by four sectors in the focal county for the site (bottom right). There are no data available for McMurdo Dry Valleys (MCM). Color of county corresponds with line color in the graphs. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

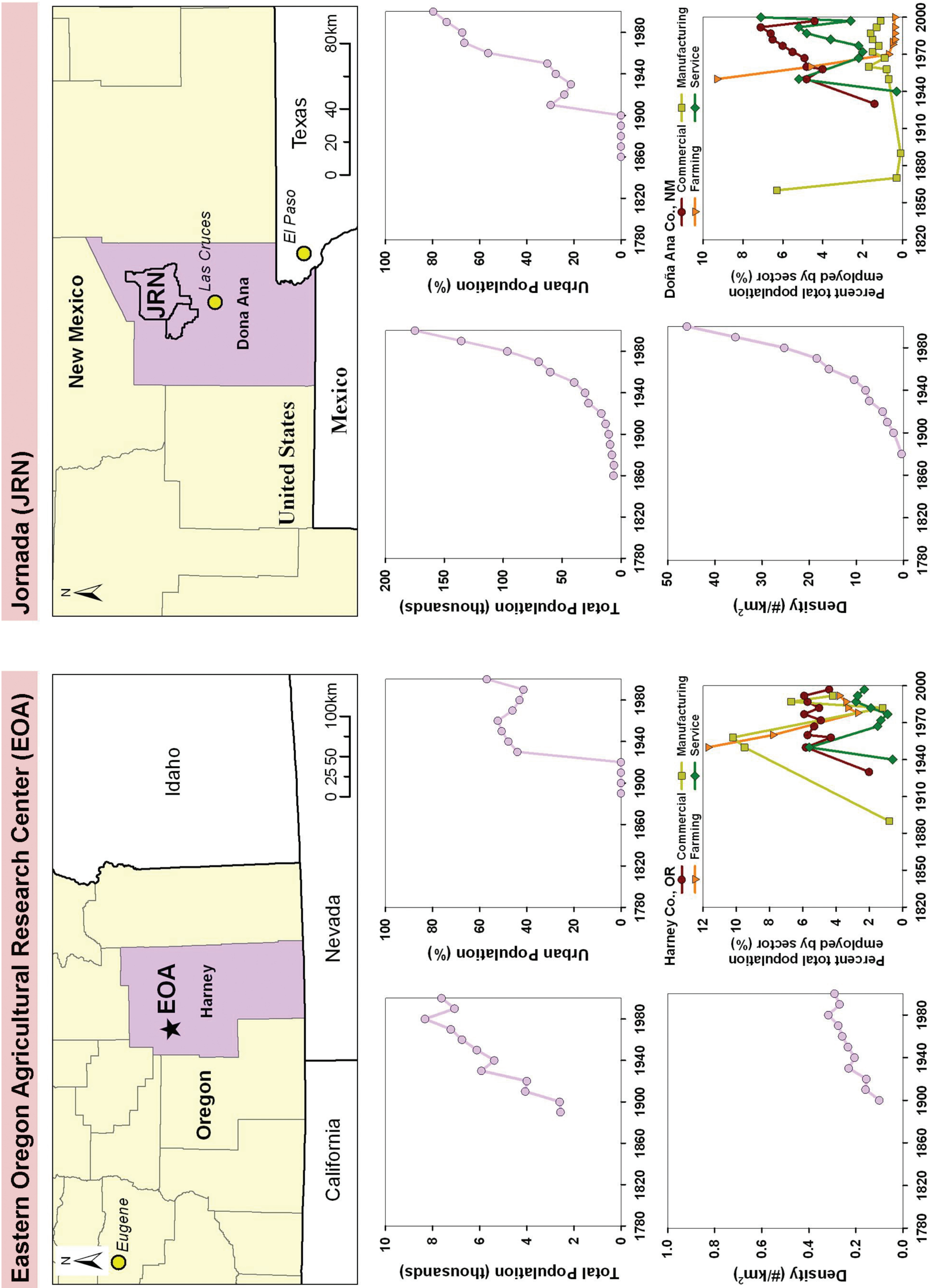


Figure 13-4 (aridland sites) continued next page.

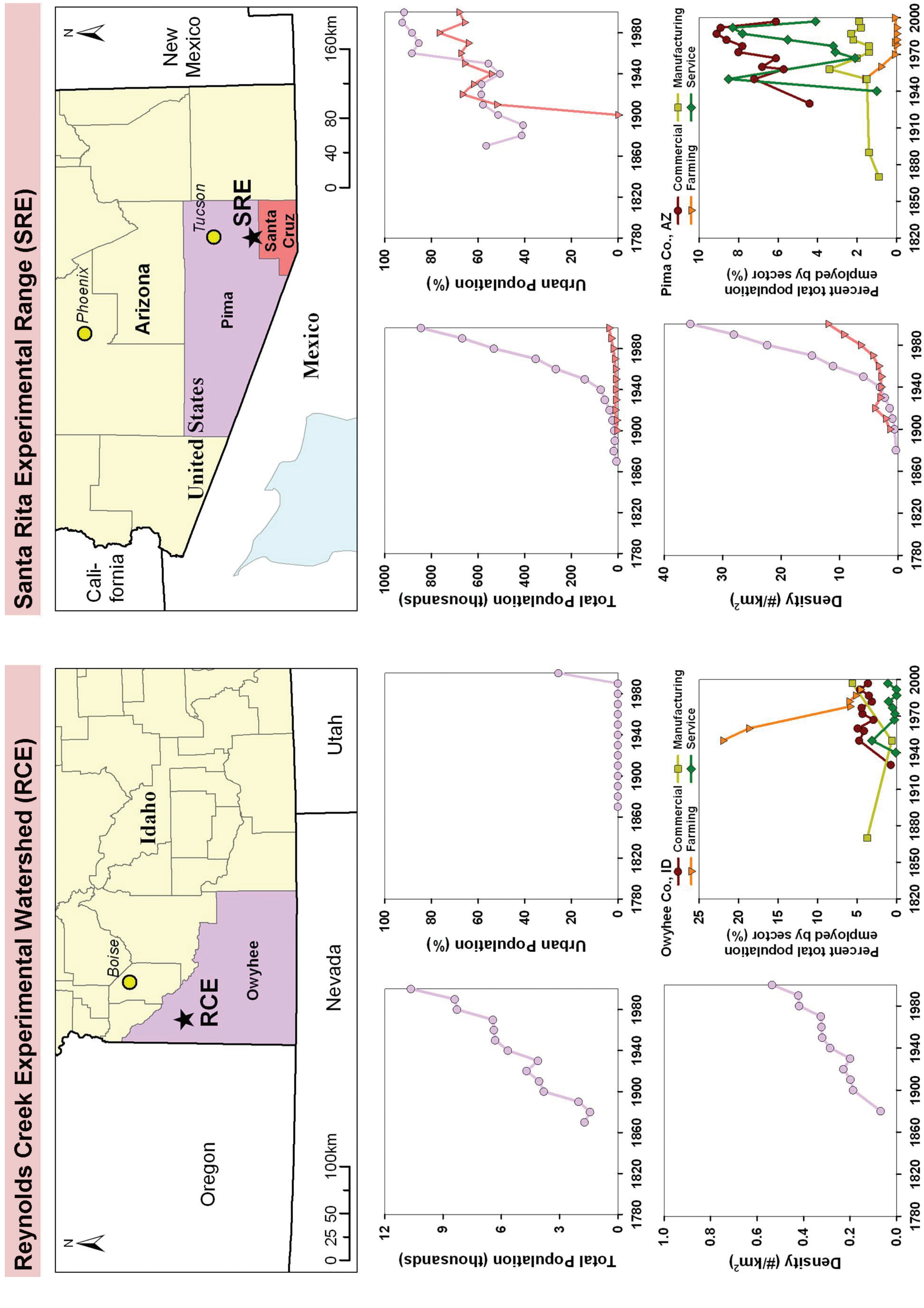


Figure 13-4 (aridland sites) continued next page.

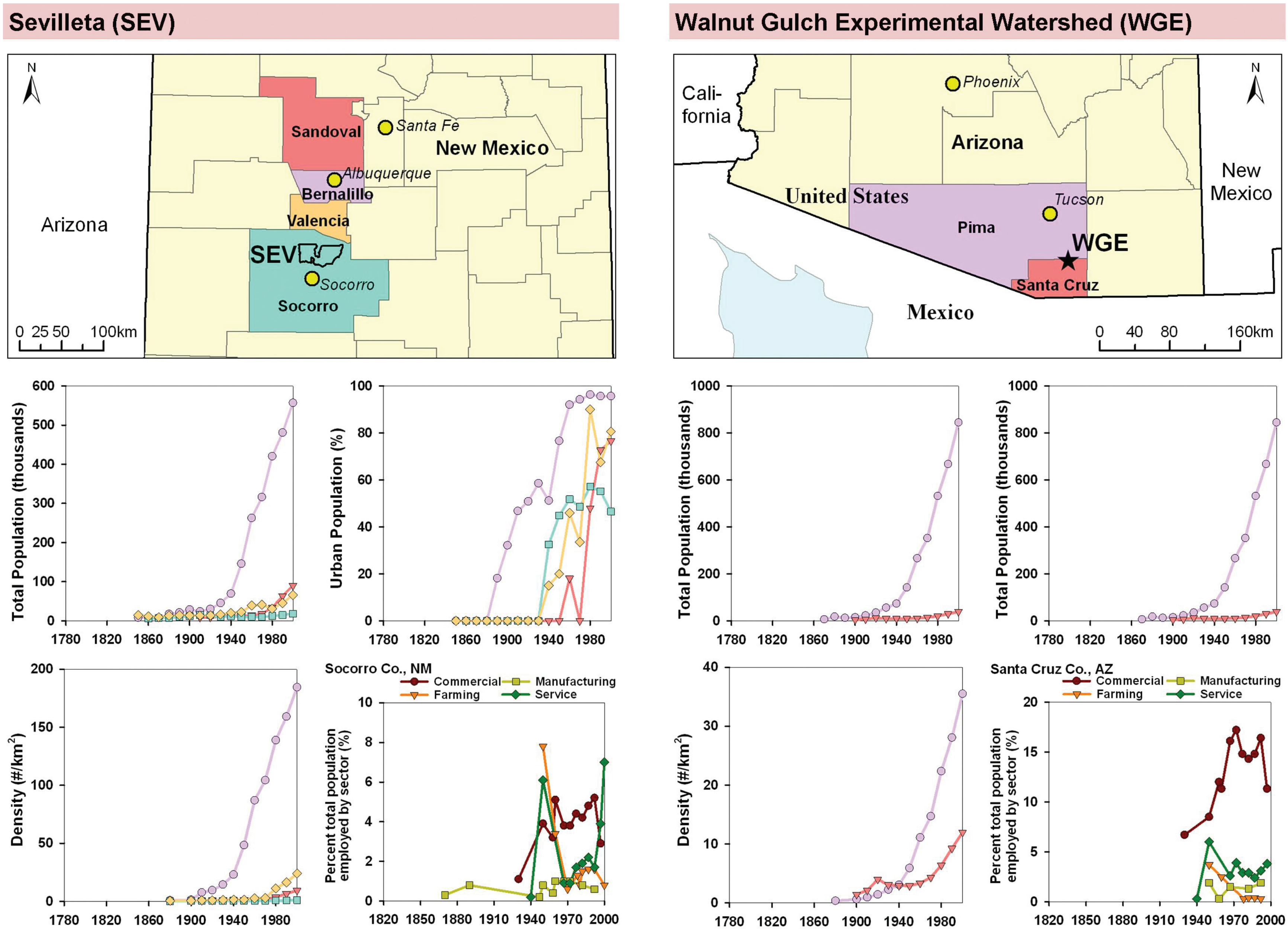


Figure 13-4. Trends for each aridland site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and percentage of total population employed by four sectors in the focal county for the site (bottom right). The Sevilleta site (SEV) also includes the middle Rio Grande riparian area from northern to central New Mexico. Color of county corresponds with line color in the graphs. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

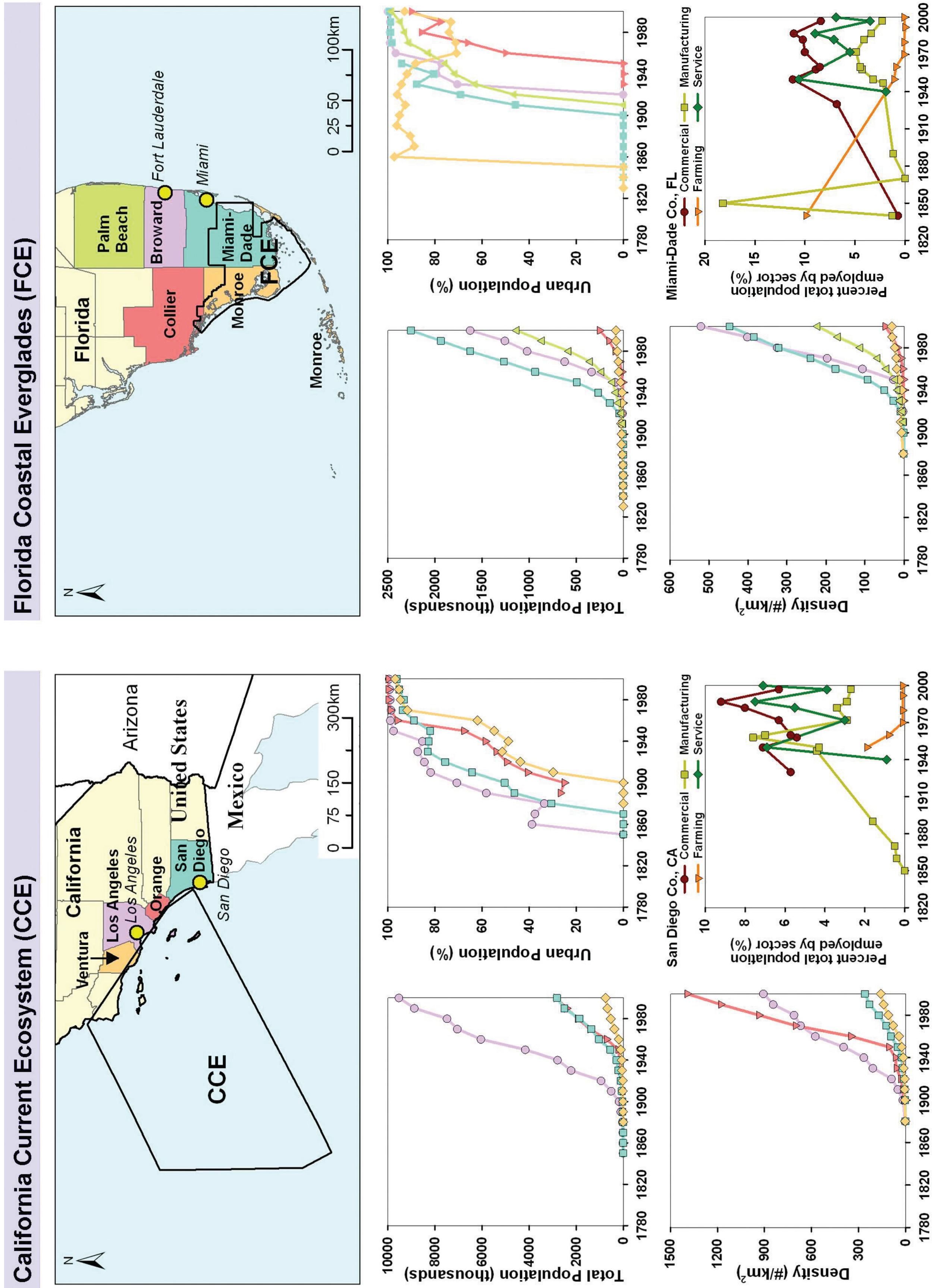


Figure 13-5 (coastal sites) continued next page.

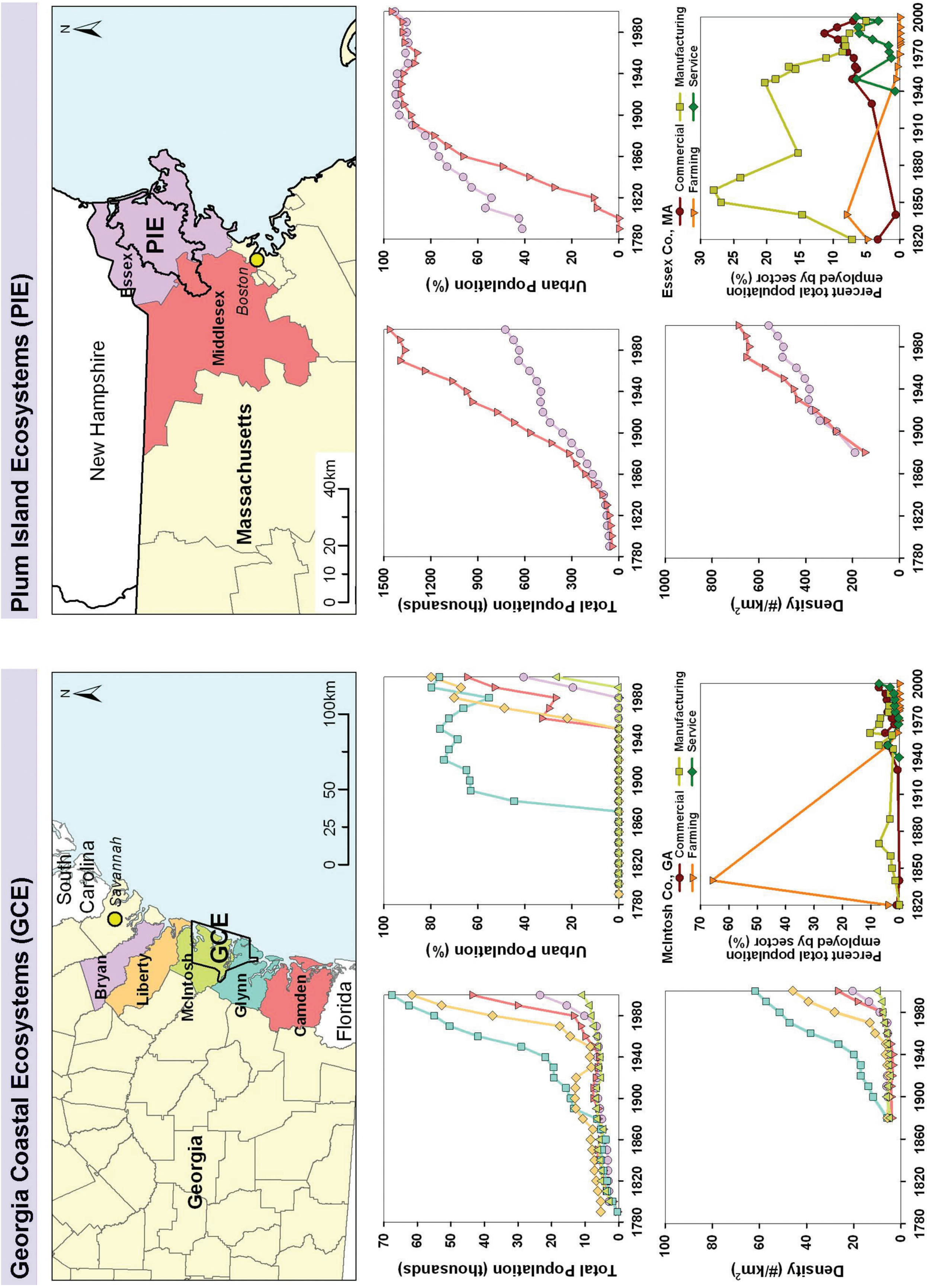


Figure 13-5 (coastal sites) continued next page.

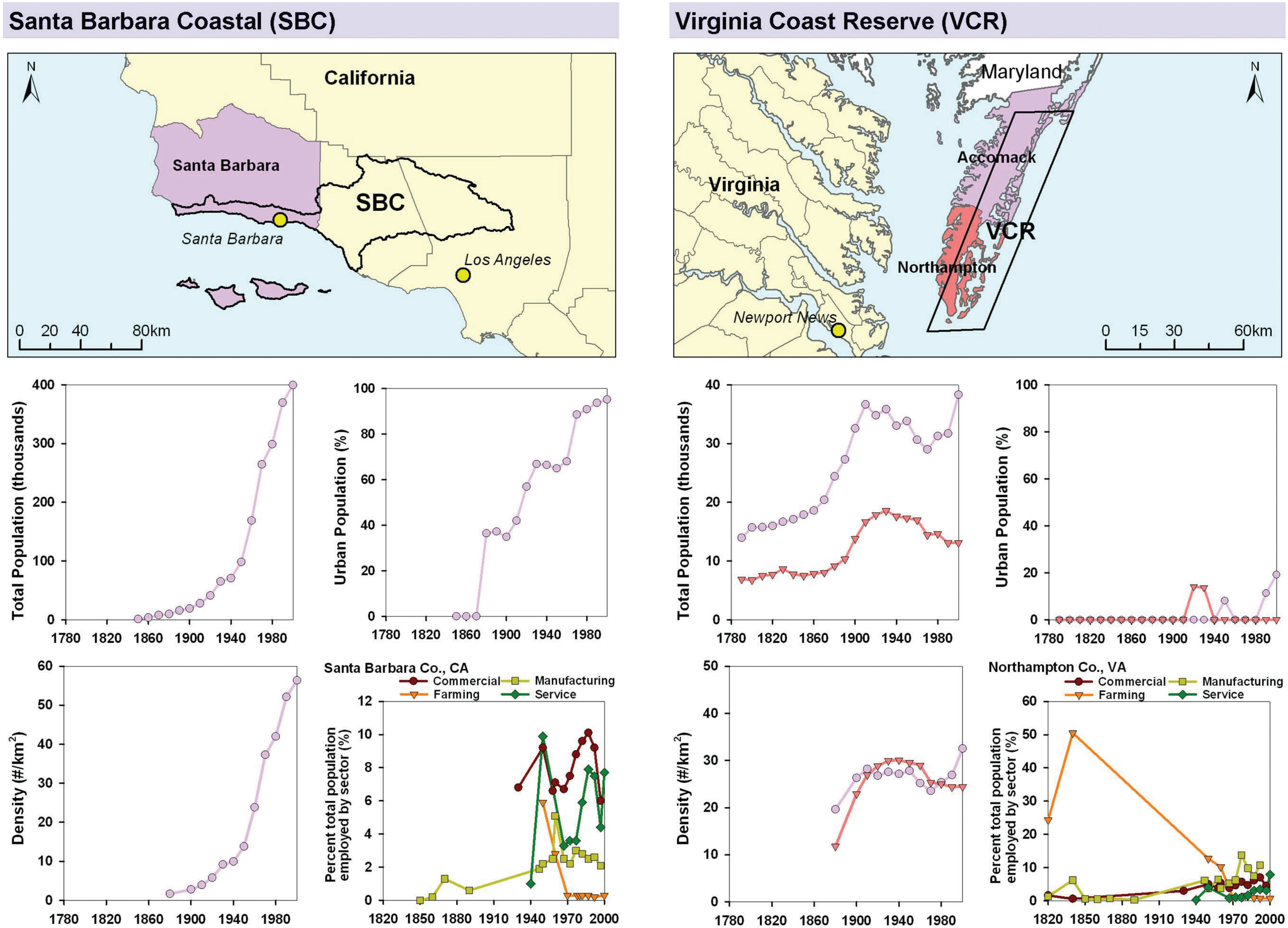


Figure 13-5. Trends for each coastal site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and percentage of total population employed by four sectors in the focal county for the site (bottom right). There are no data available for Moorea Coral Reef (MCR) and Palmer Station (PAL). Color of county corresponds with line color in the graphs. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

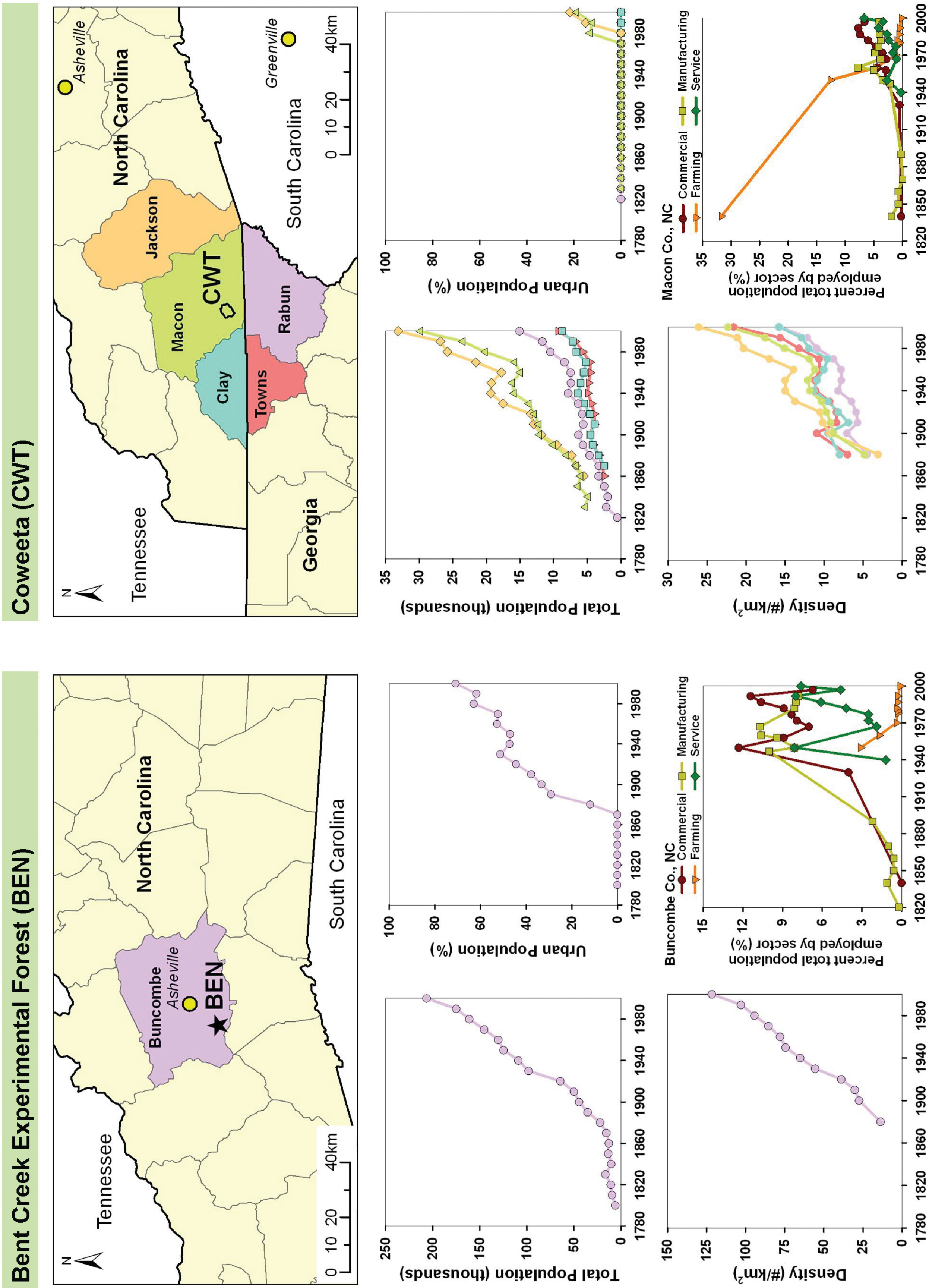
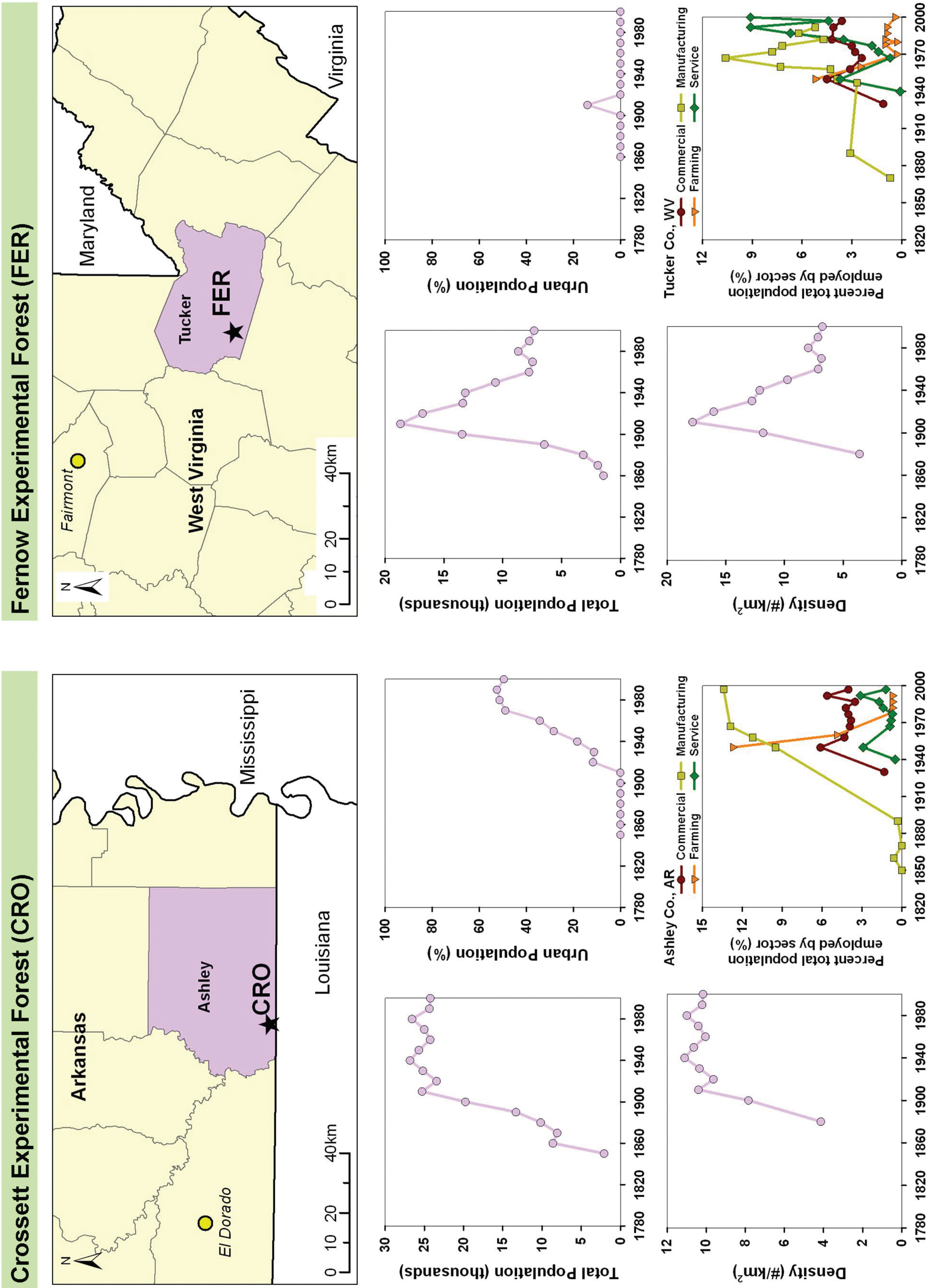


Figure 13-6 (eastern forest sites) continued next page.



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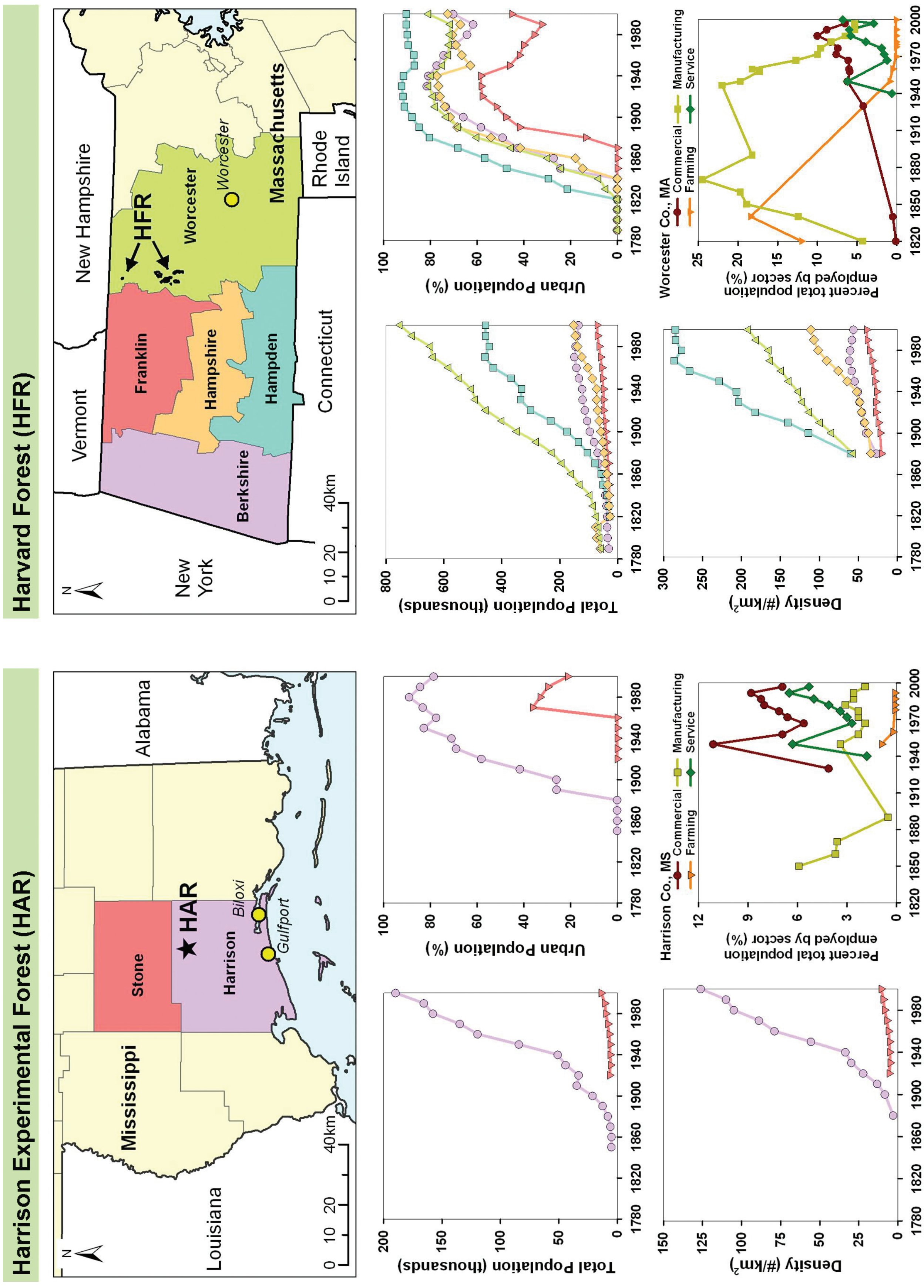

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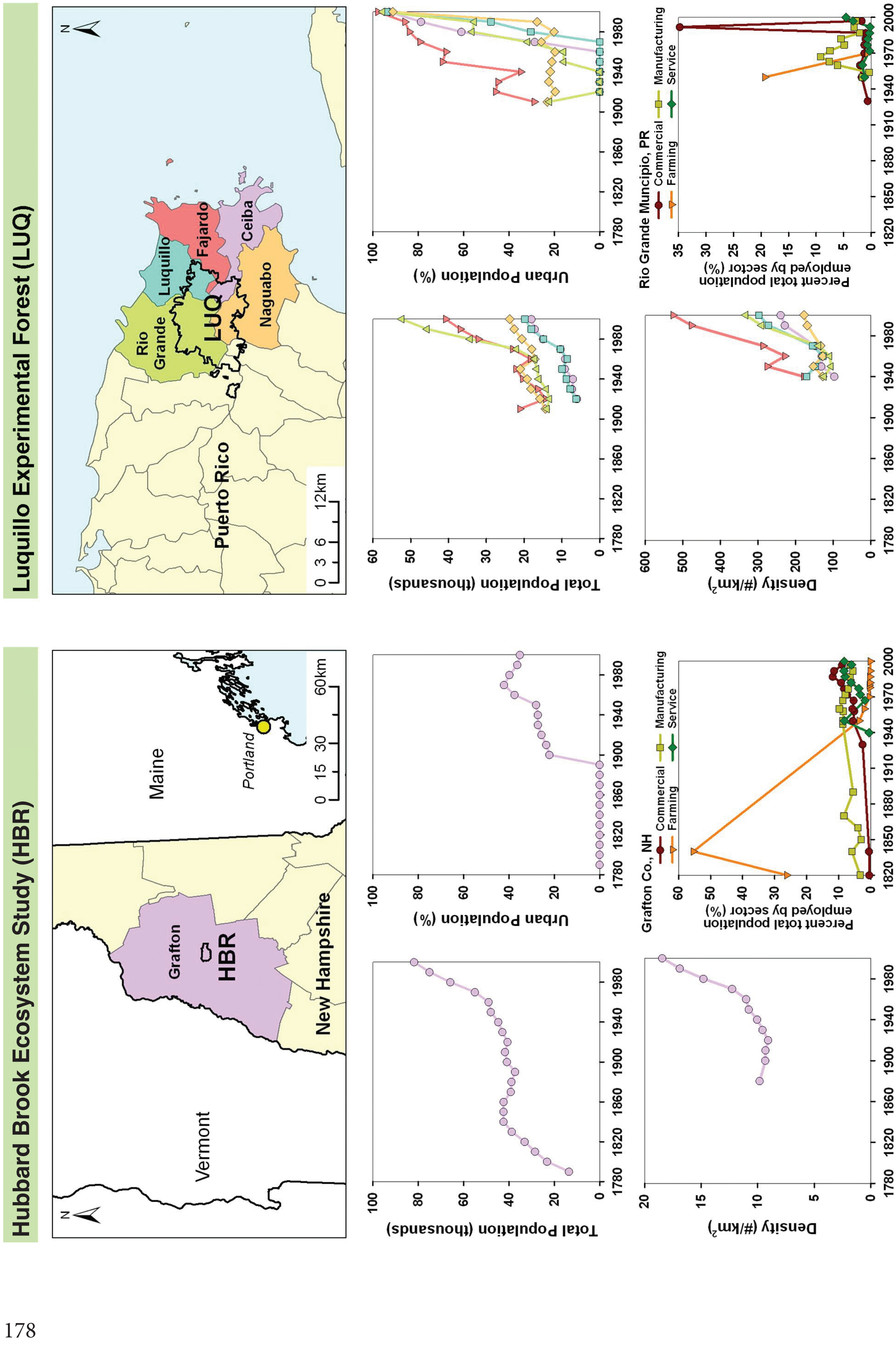

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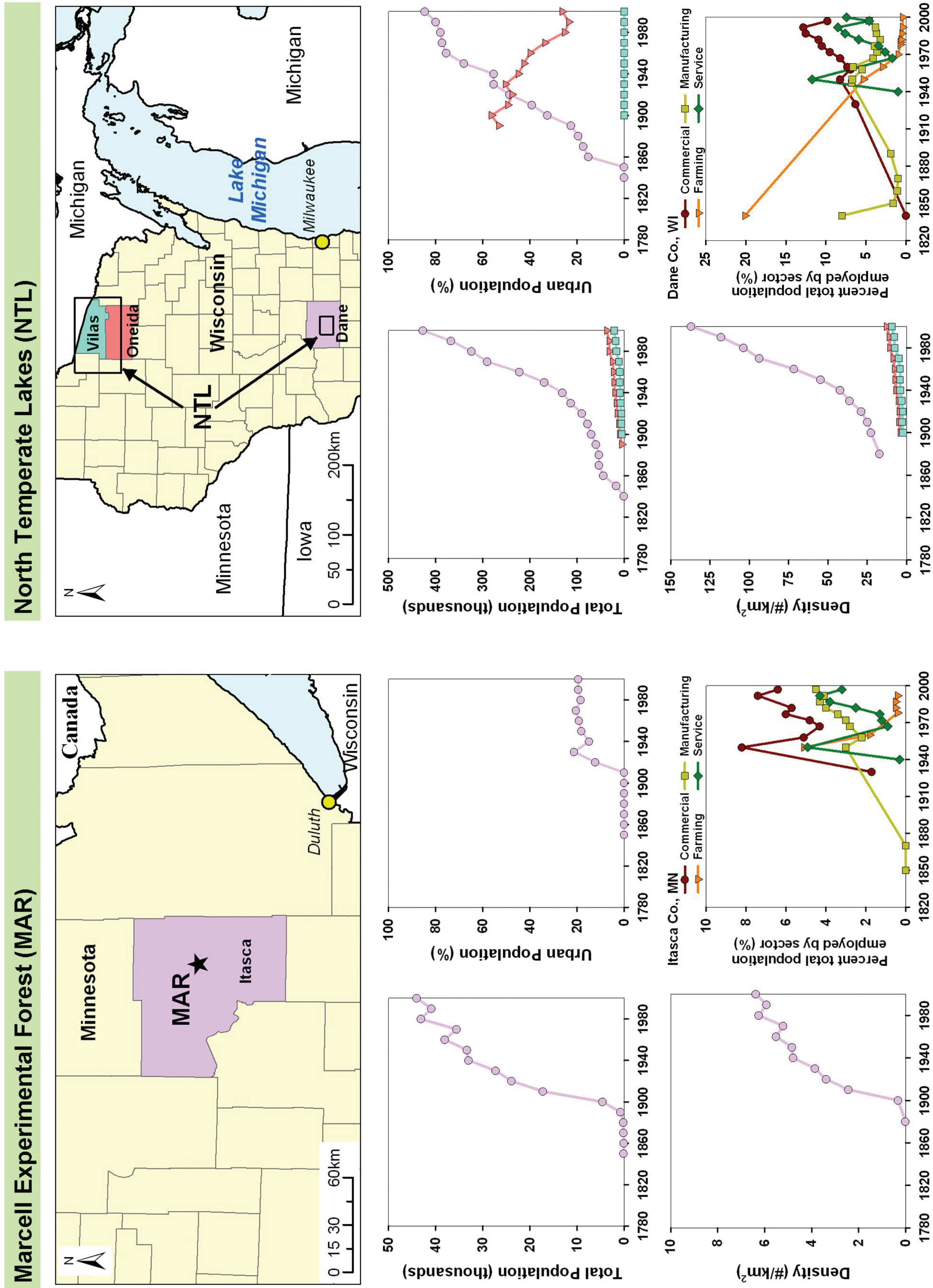

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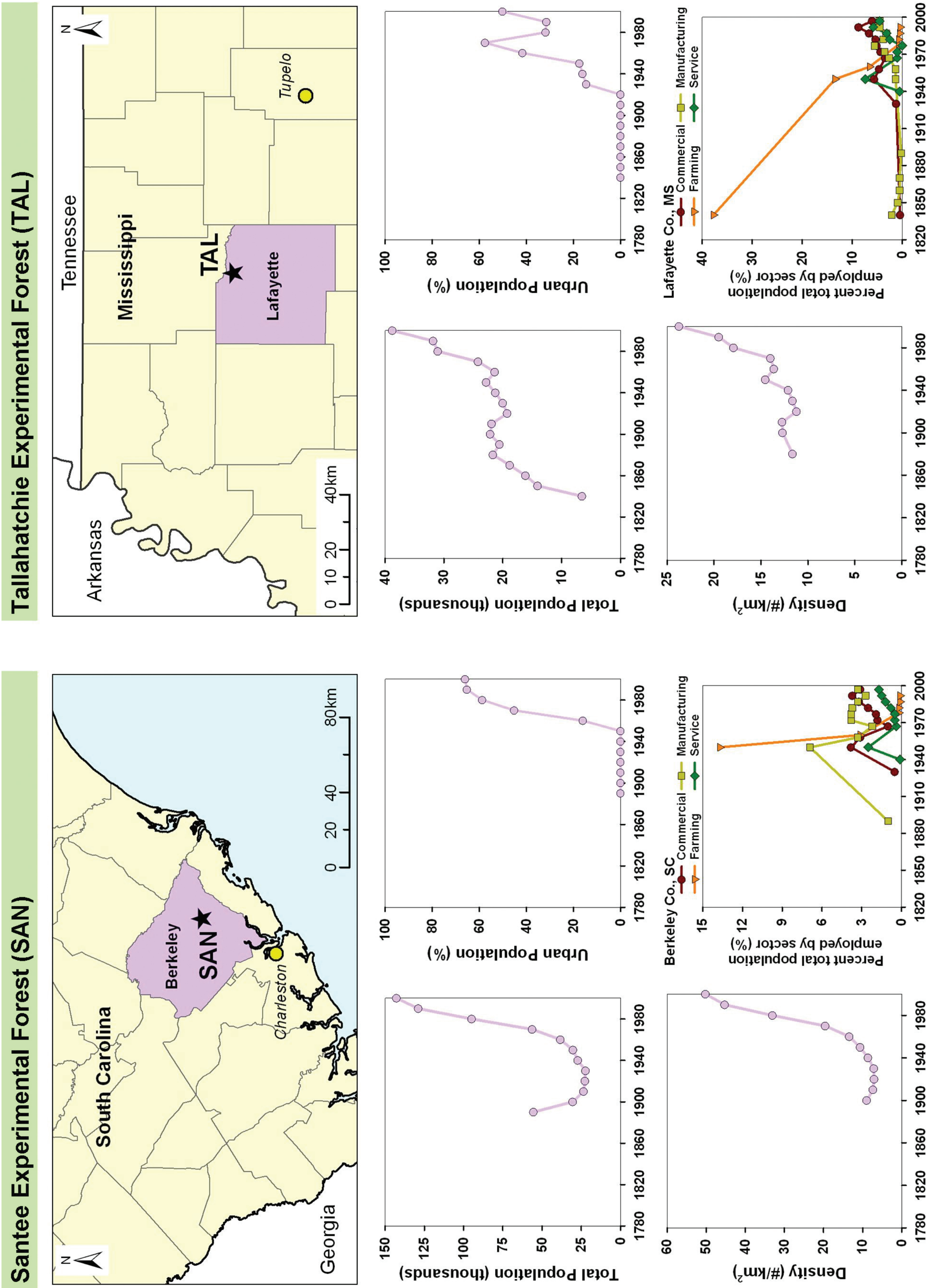

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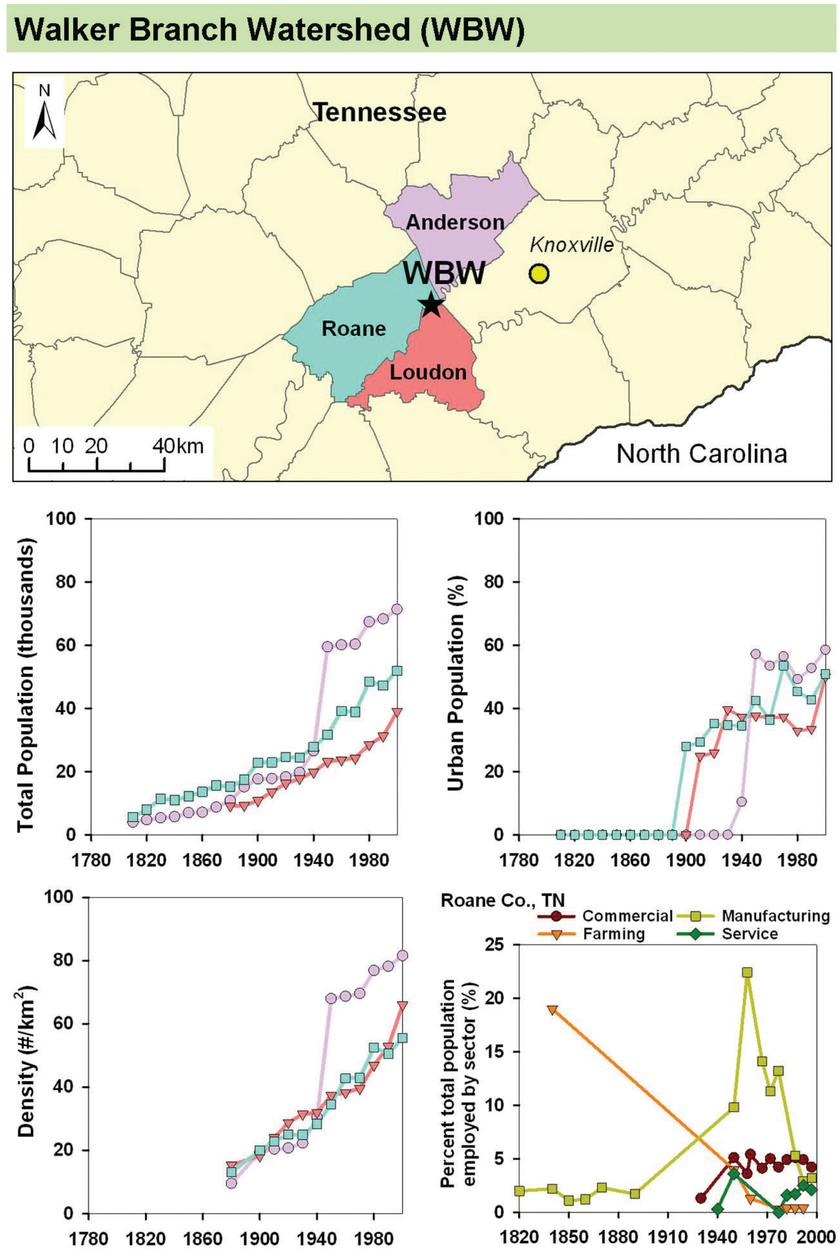


Figure 13-6. Trends for each eastern forest site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and (bottom right) percentage of total population employed by four sectors in the focal county for the site. Color of county corresponds with line color in the graphs. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

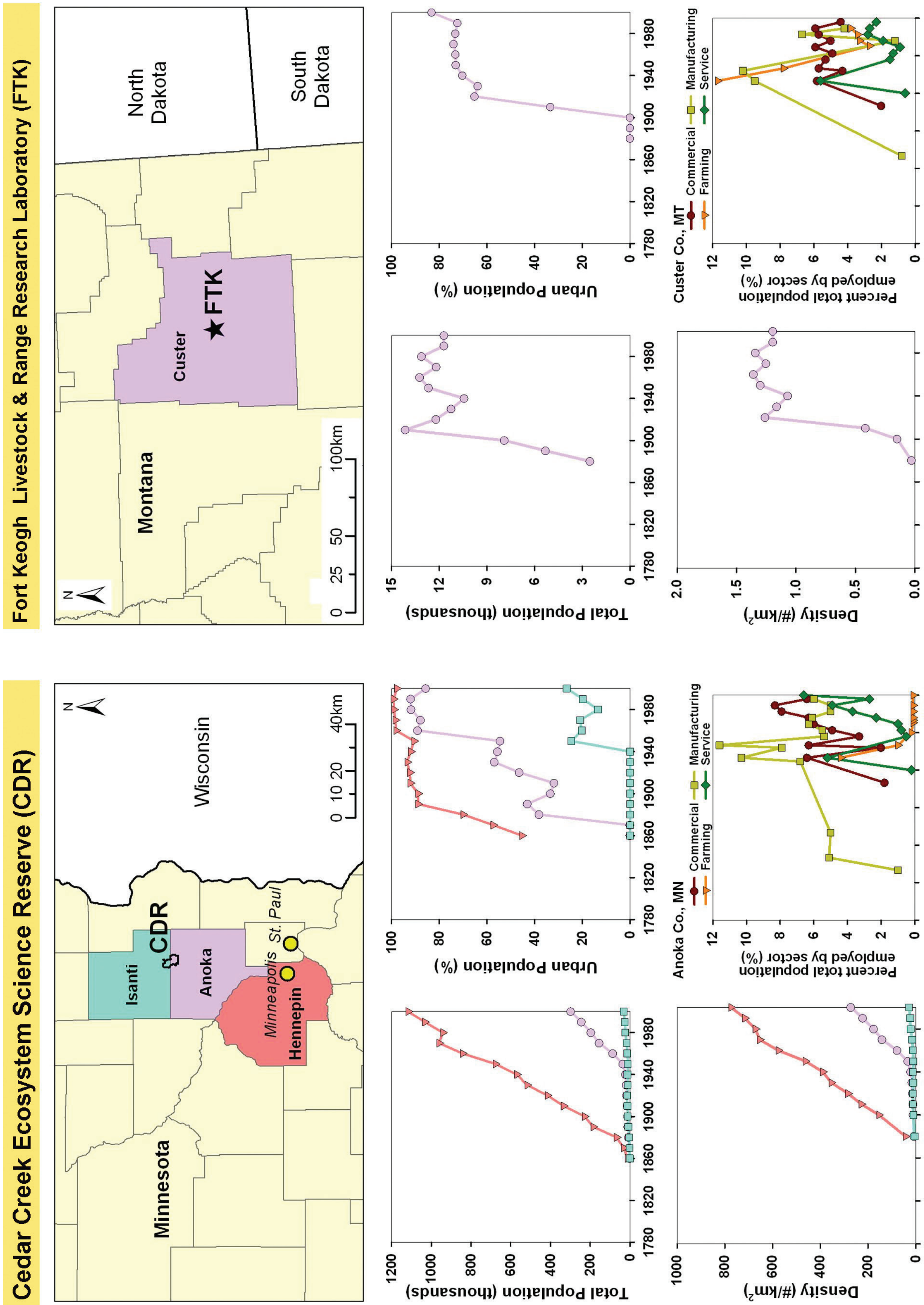


Figure 13-7 (grassland and savanna sites) continued next page.

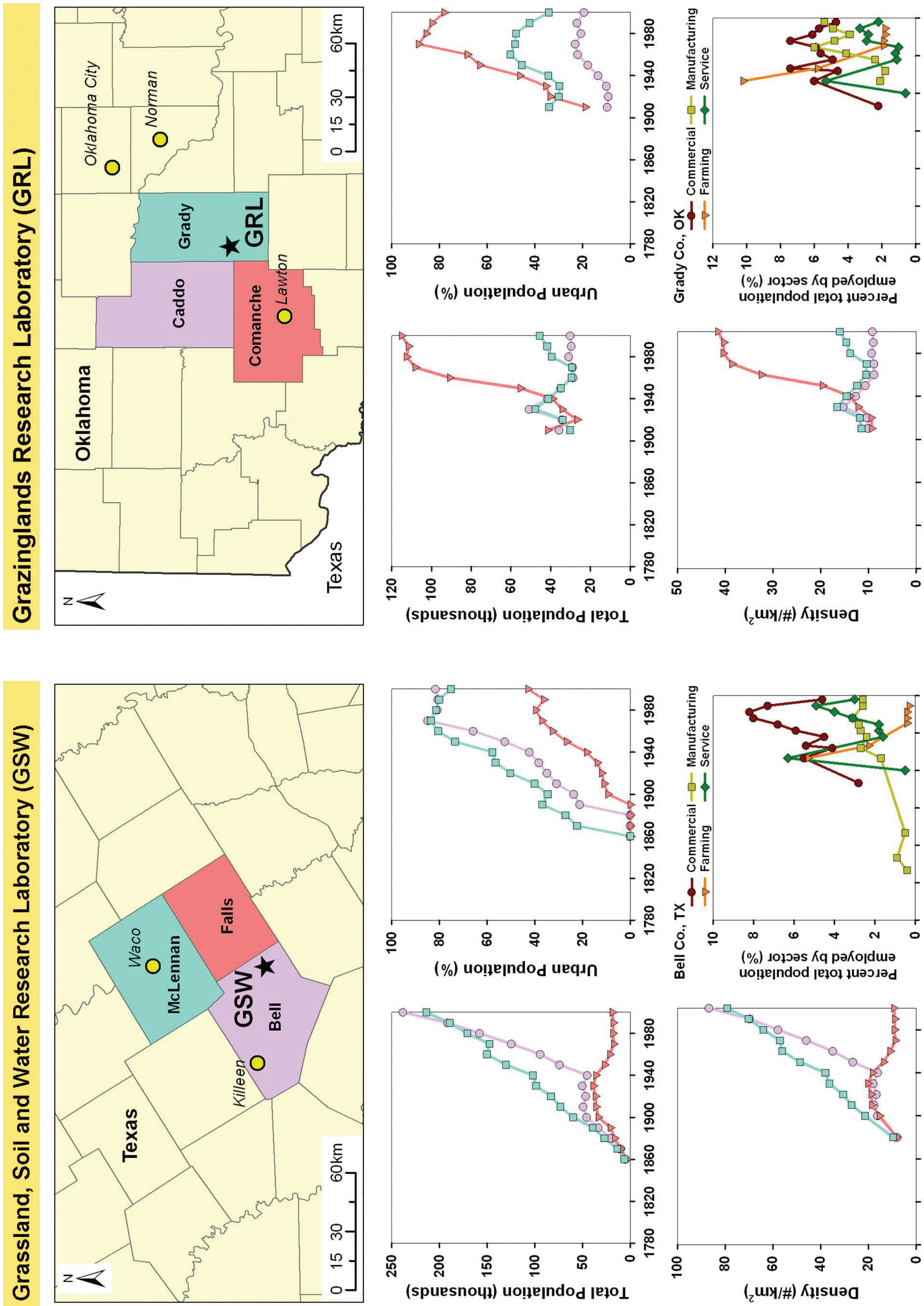


Figure 13-7 (grassland and savanna sites) continued next page.

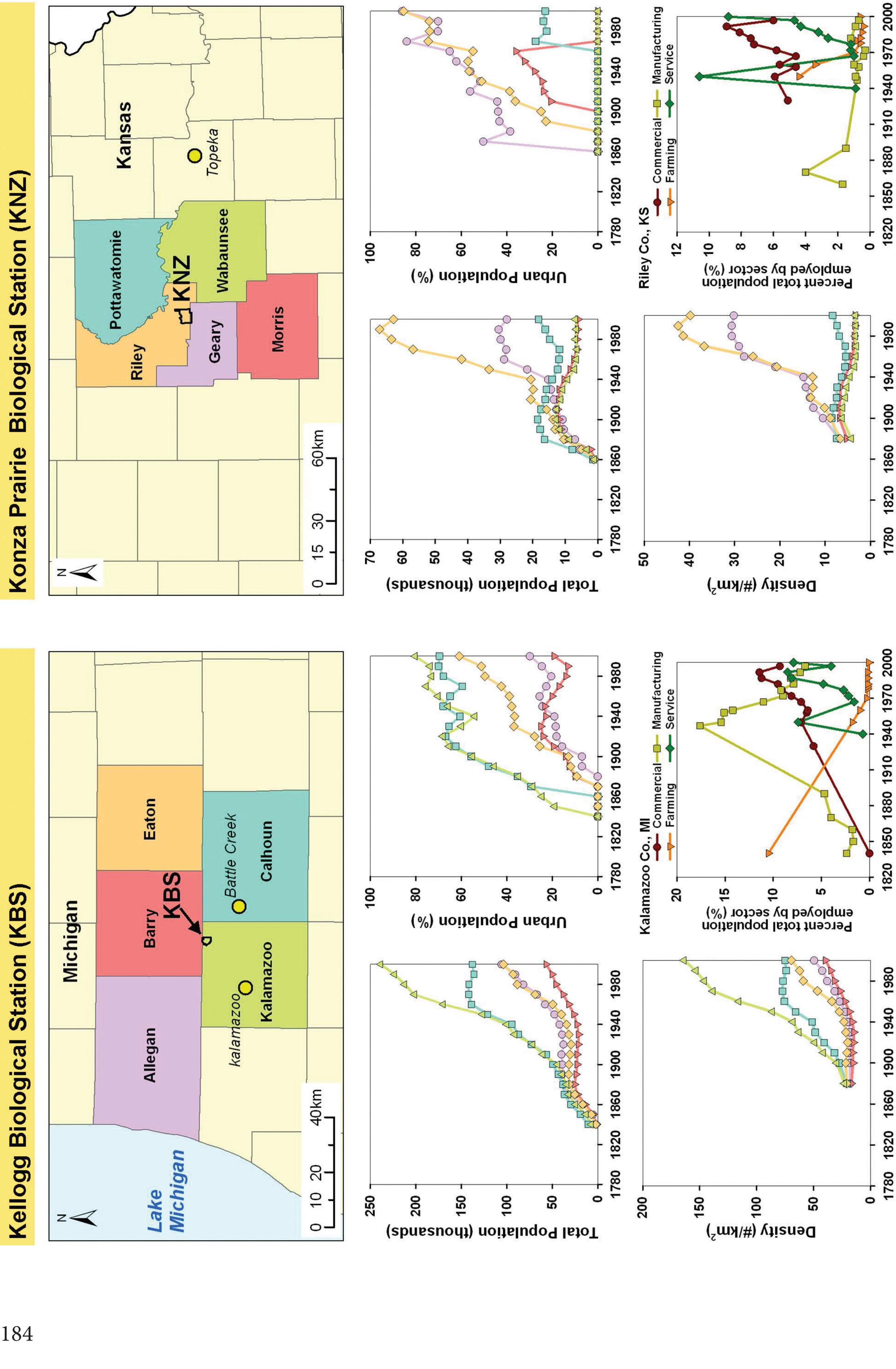


Figure 13-7 (grassland and savanna sites) continued next page.

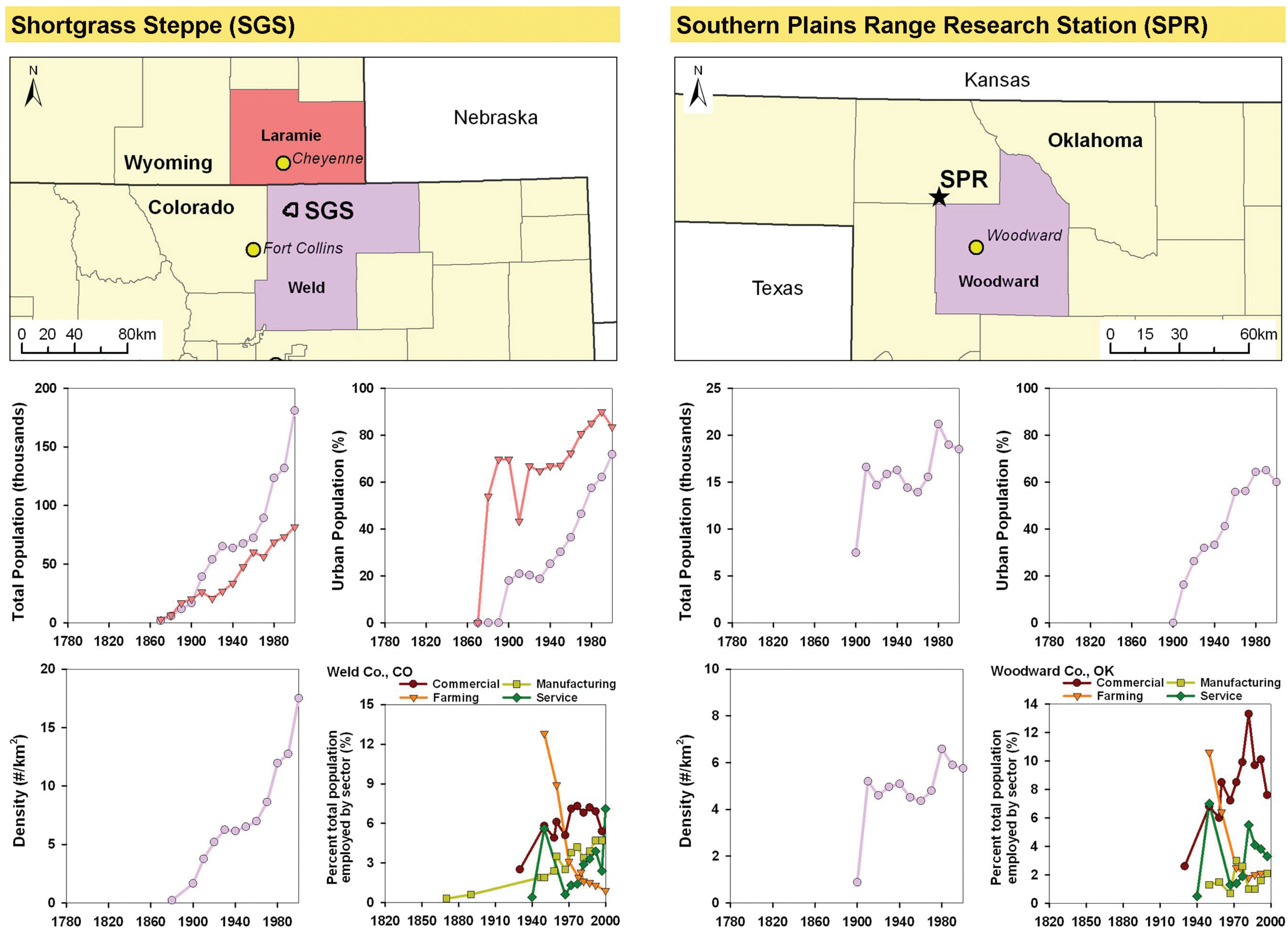


Figure 13-7. Trends for each temperate grassland and savanna site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and percentage of total population employed by four sectors in the focal county for the site (bottom right). Color of county corresponds with line color in the graphs. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

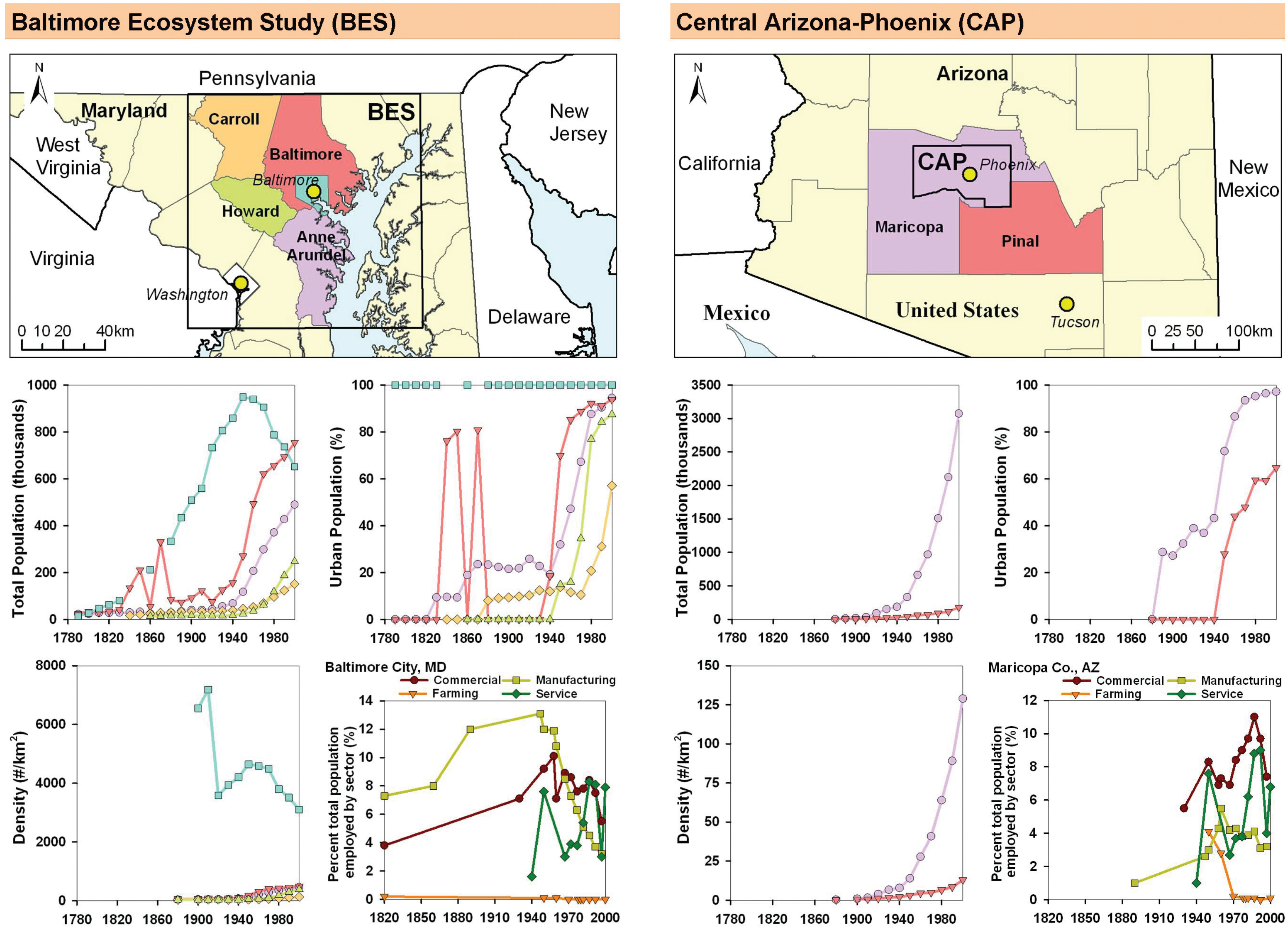


Figure 13-8. Trends for each urban site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and percentage of total population employed by four sectors in the focal county for the site (bottom right). Color of county corresponds with line color in the graphs. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

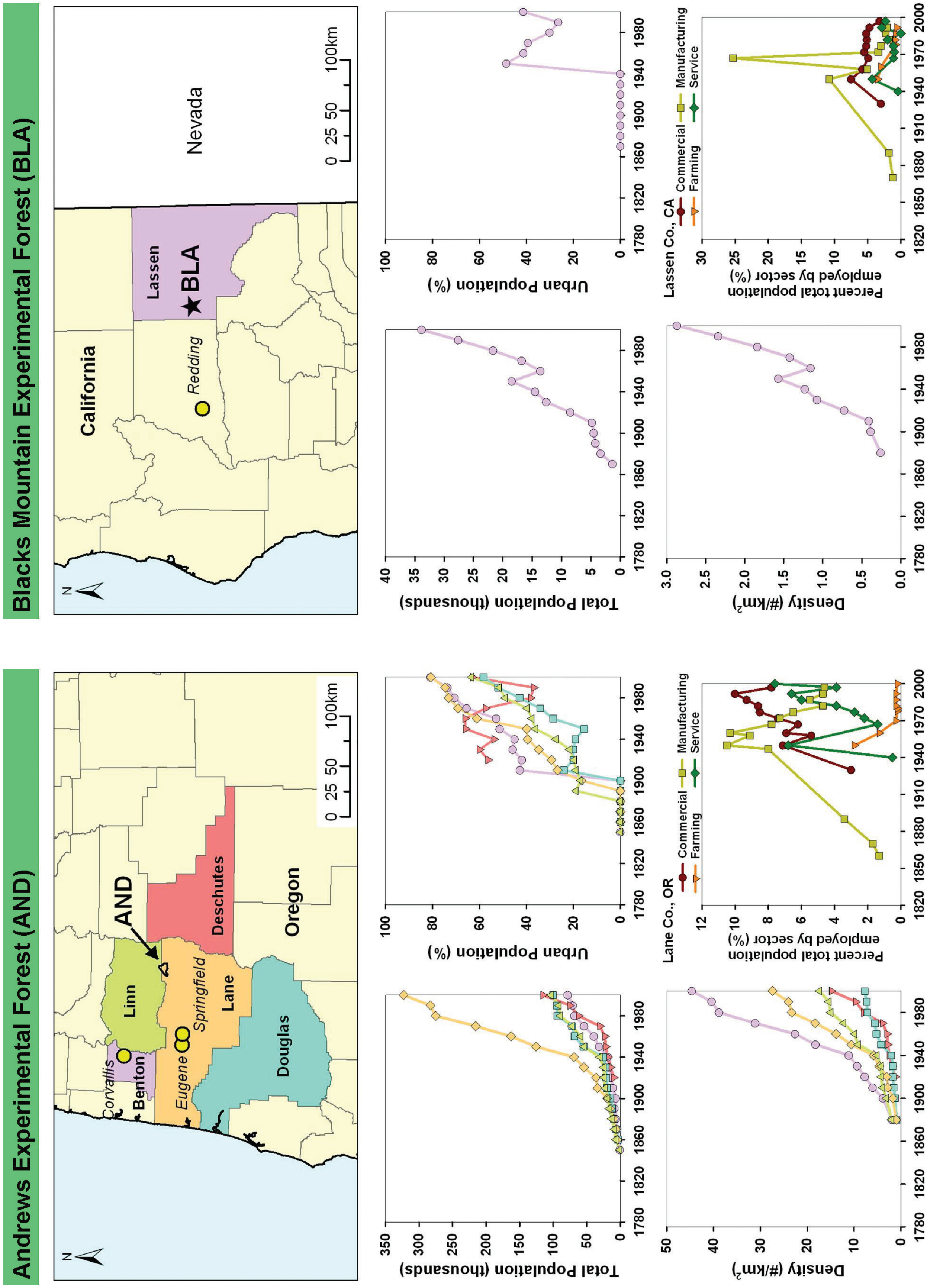
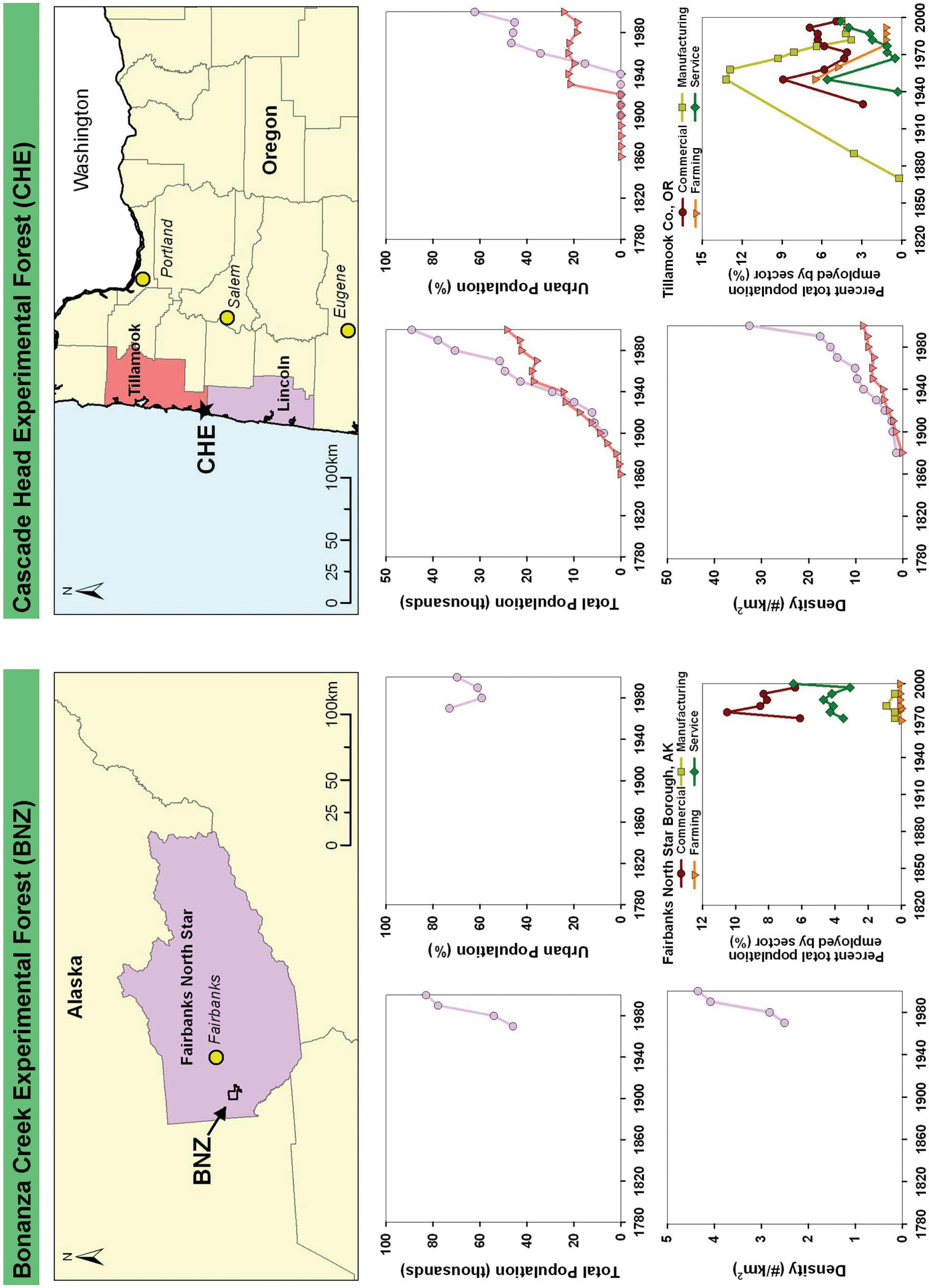


Figure 13-9 (western forest sites) continued next page.



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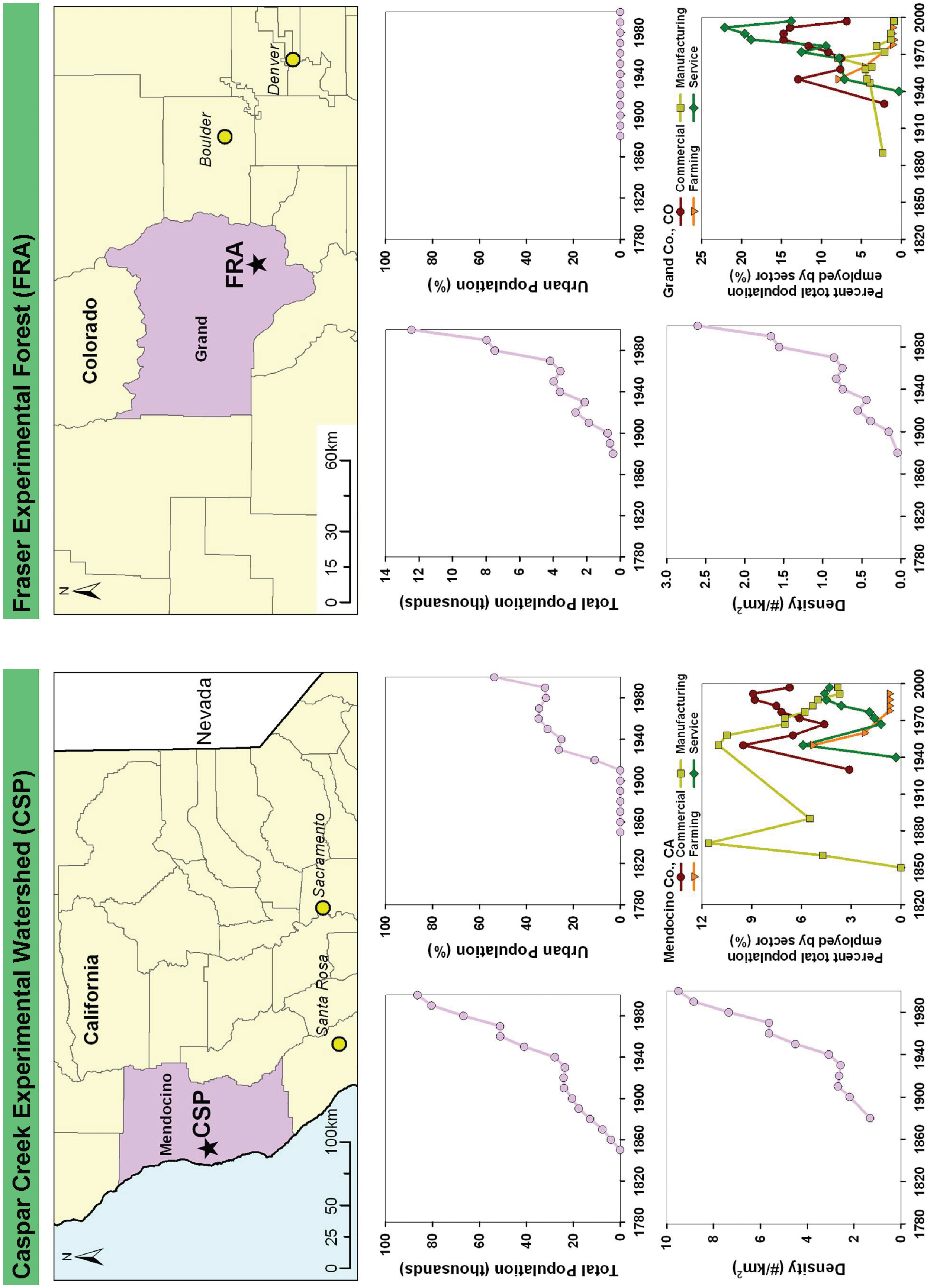

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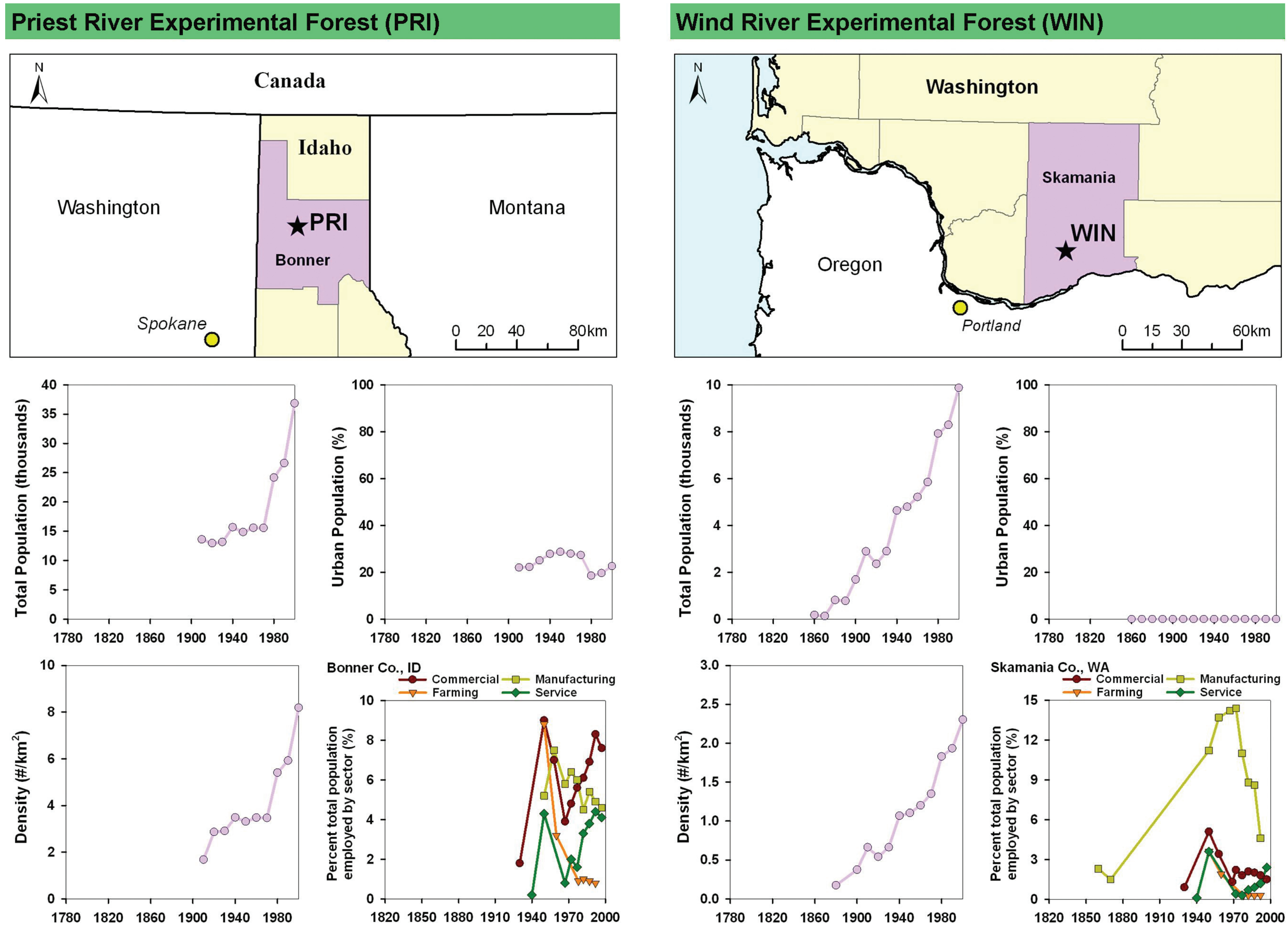

Figure 13-9. Trends for each western forest site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and percentage of total population employed by four sectors in the focal county for the site (bottom right). Color of county corresponds with line color in the graphs. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

Chapter 14

Long-Term Trends in Production, Abundance, and Richness of Plants and Animals

Trends in biotic structure have been of interest in the United States since the establishment of the Division of Biological Survey in the U.S. Department of Agriculture in the late 1890s. Changes in biotic structure can serve as a bellwether for quantifying the effects of climate change, land-use change, and the spread of exotic species, as well as the loss of rare and endangered species. Considerable evidence suggests that changes in biotic structure can have significant consequences for ecosystem functioning and the provisioning of ecosystems goods and services.

In this chapter, we first describe common methods for measuring responses of plants and animals and our rationale for the selection of variables included in this book. We then show graphs of biotic data through time for each site arrayed across the continent.

Methods of Measurements and Selection of Variables

Biotic structure can be characterized by a wide array of variables, but we limit our discussion to those variables that represent key components of ecological systems. One of the most important variables in all ecosystems is net primary production (NPP), the accumulation of biomass over a specified time period, usually seasonally or annually. NPP represents the amount of energy fixed by producers (for example, vascular plants or algae) that can be used for their growth and reproduction and that is available for consumption by herbivores. Life on Earth depends on this conversion of inorganic compounds to organic molecules and the release of oxygen; thus NPP is a critical variable for all ecosystems, even though the primary producers vary from vascular plants on land to algae and phytoplankton in the lakes and oceans. Terrestrial NPP consists of both aboveground (ANPP) and belowground (BNPP) components, although ANPP is the most commonly measured in long-term studies (chapter 5).

Other variables of particular importance are the biomass, cover, and density of key species and groups of similar species (that is, functional groups) that represent each ecosystem. Biomass is the mass per unit area of living material (plants, animals, microbes), typically measured as grams per square meter (g/m^2) or kilograms per hectare (kg/ha). Changes in biomass over time are often used to calculate NPP. Biomass is a measure of stored energy (in wood, sugar cane, corn, for example) and carbon that is sequestered from the atmosphere. Cover is the amount of surface area occupied by plants or animals and is often represented as a percentage of the total area (for instance, [m^2 leaf area ÷ m^2 ground area] × 100). Density is the number of individuals found in a unit of area, such as number per square meter or per hectare.

Biomass, cover, or density can be used as estimates of the abundance of organisms and species composition (the percentage that each species contributes to a measurement). Species richness, the number of species in an area (such as per m^2), is an important measure of biodiversity. Species richness is available for some sites, although differences in sampling area often result in difficulties in comparing across sites.

The long-term biotic structure data represent a somewhat eclectic set of species on which, for the most part, the same measurements are rarely collected at all sites—in contrast to climatic, biogeochemical, and human population data (chapters 11-13). This diversity of species is to be expected given the uniqueness of the biota across the broad range of sites represented in the EcoTrends database. Also, a research philosophy that originally helped structure the LTER Network was a focus on core research areas relevant to each site. One of these areas was the measurement of the spatial and temporal distribution of populations selected to represent trophic structure within a given ecosystem. As a consequence, most LTER sites have quantitative data on plant community composition and structure, but many different kinds of consumer species are represented in figures14-1 to 14-12. In many cases, the graphs present aggregate variables (species richness, total abundance); however, data on long-term species trends are available on the EcoTrends website (http://www.ecotrends.info).

At most sites, NPP is shown in comparable units, such as grams/m^2/year, despite a variety of measurement techniques. For terrestrial ecosystems, most sites only estimate long-term ANPP; difficulties in obtaining accurate and cost-effective estimates of BNPP result in very few, if any, long-term datasets of this variable. Repeated clipping of herbaceous biomass or estimations of changes in plant sizes are often used in grasslands and deserts to estimate ANPP. Diameter at breast height (DBH) or basal area increment (BAI) and annual litterfall are most often used in forests. Chlorophyll content or measurement of either O_2 or CO_2 consumption or production in light and dark bottles can be used as surrogates for NPP in aquatic systems. Although the methods in terrestrial and aquatic systems are highly disparate, all measurements can be converted to common units for cross-system comparisons. At very large spatial scales, satellite data and remotely sensed images can be used to estimate "greenness" which can be correlated with NPP in freshwater, marine, and terrestrial systems.

Similarly, the measurements of species composition and abundance also differ among terrestrial and aquatic systems, as well as in different types of ecosystem. These differences are reflected in the different units of measure on the graphs below.

Graphs Showing Long-Term Trends

The remainder of this chapter is devoted to showing trends in plant and animal variables by site across the continent. For plants, we focus on four variables that are often measured at many sites: species richness, ANPP, biomass, and DBH. For animals, we include species richness of birds, insects, and fish and abundance of birds, insects, and small mammals. Data are shown annually through time, and a regression line is shown if the relationship was significant ($p < 0.05$) and the trend appears linear. Long-term means and regression coefficients can be found in appendices 16 through 23.

Summary

At many sites, multiple locations are sampled for plant and animal dynamics. The large within-site variability in responses often overwhelms trends through time. Although plant response variables of ANPP, richness, and biomass are sampled for most LTER sites to allow cross-site comparisons, animal response variables are more variable among sites with fewer comparable groups. These results reflect the underlying organizational structure of the LTER to select representative trophic groups from a site rather than attempting to standardize across sites. The length of the time series also varies across sites, which further complicates cross-site comparisons.

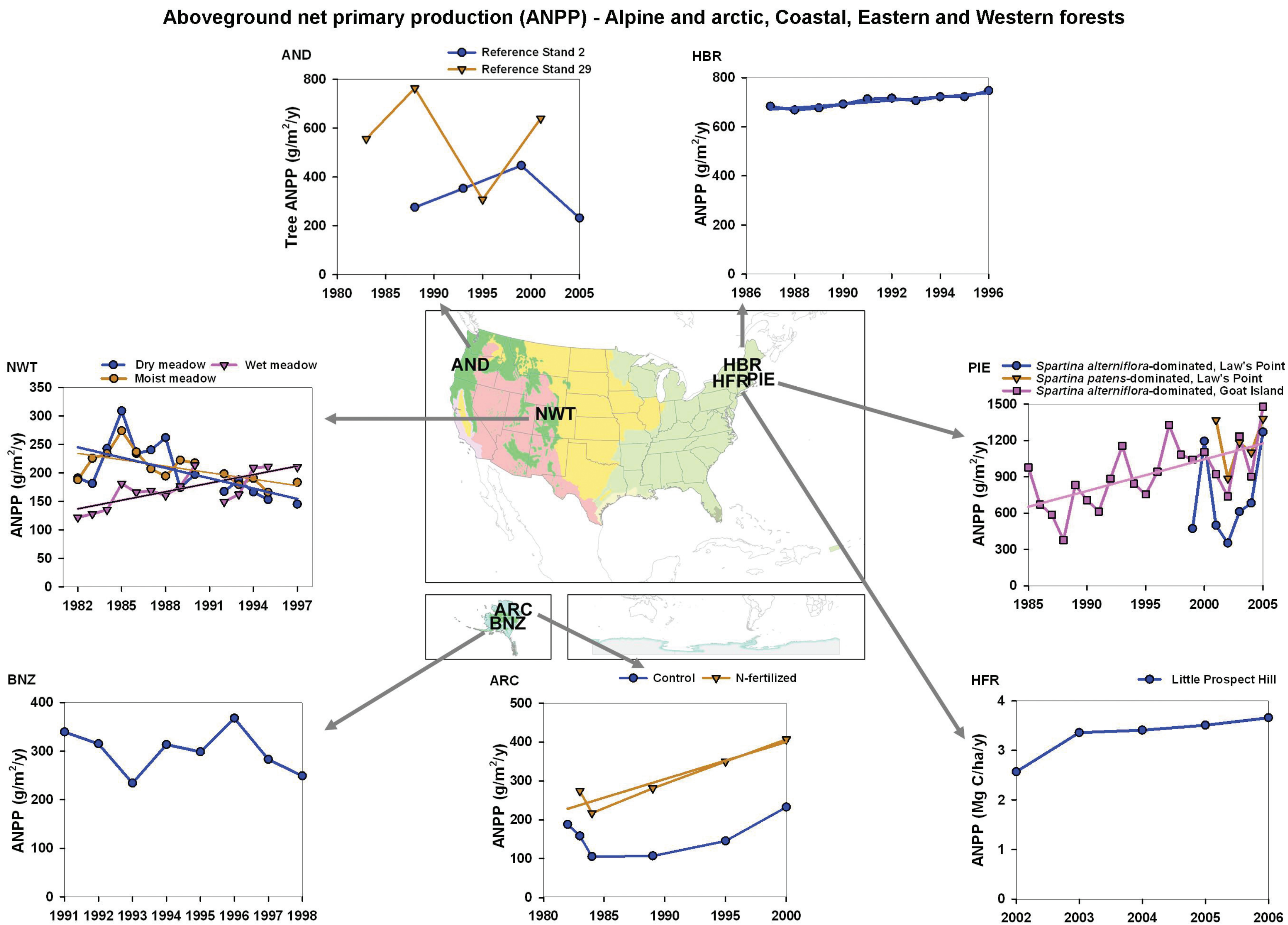

Figure 14-1. Aboveground net primary production (ANPP, g/m²/y or Mg C/ha/y) for arctic and alpine (ARC and NWT), coastal (PIE), and eastern and western forest (AND, BNZ, HBR, and HFR) sites. A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are: ARC (10), HBR (7), NWT (-6, -4, 5), and PIE (26). Original data from Internet home pages (see table 1-1). Synthesized data from http://www.ecotrends.info.

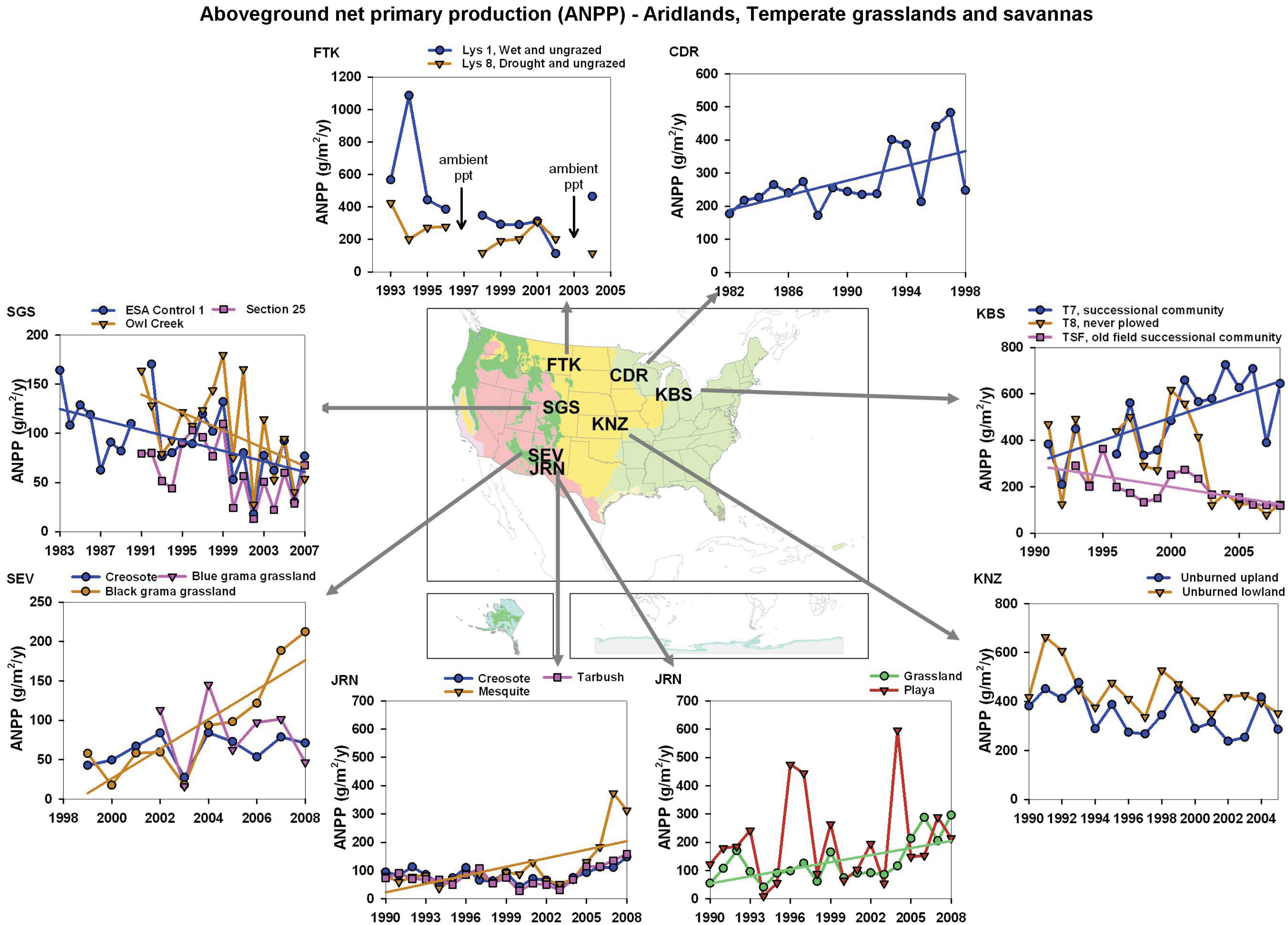

Figure 14-2. Aboveground net primary production (ANPP, g/m²/y) for aridland (FTK, JRN, SEV, and SGS) and temperate grassland/savanna (CDR, KBS, and KNZ) sites. A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are CDR (11), JRN (8, 10), KBS (22, -10), SEV (19), and SGS (-3, -5). Original data from Internet home pages (see table 1-1). Synthesized data from http://www.ecotrends.info.

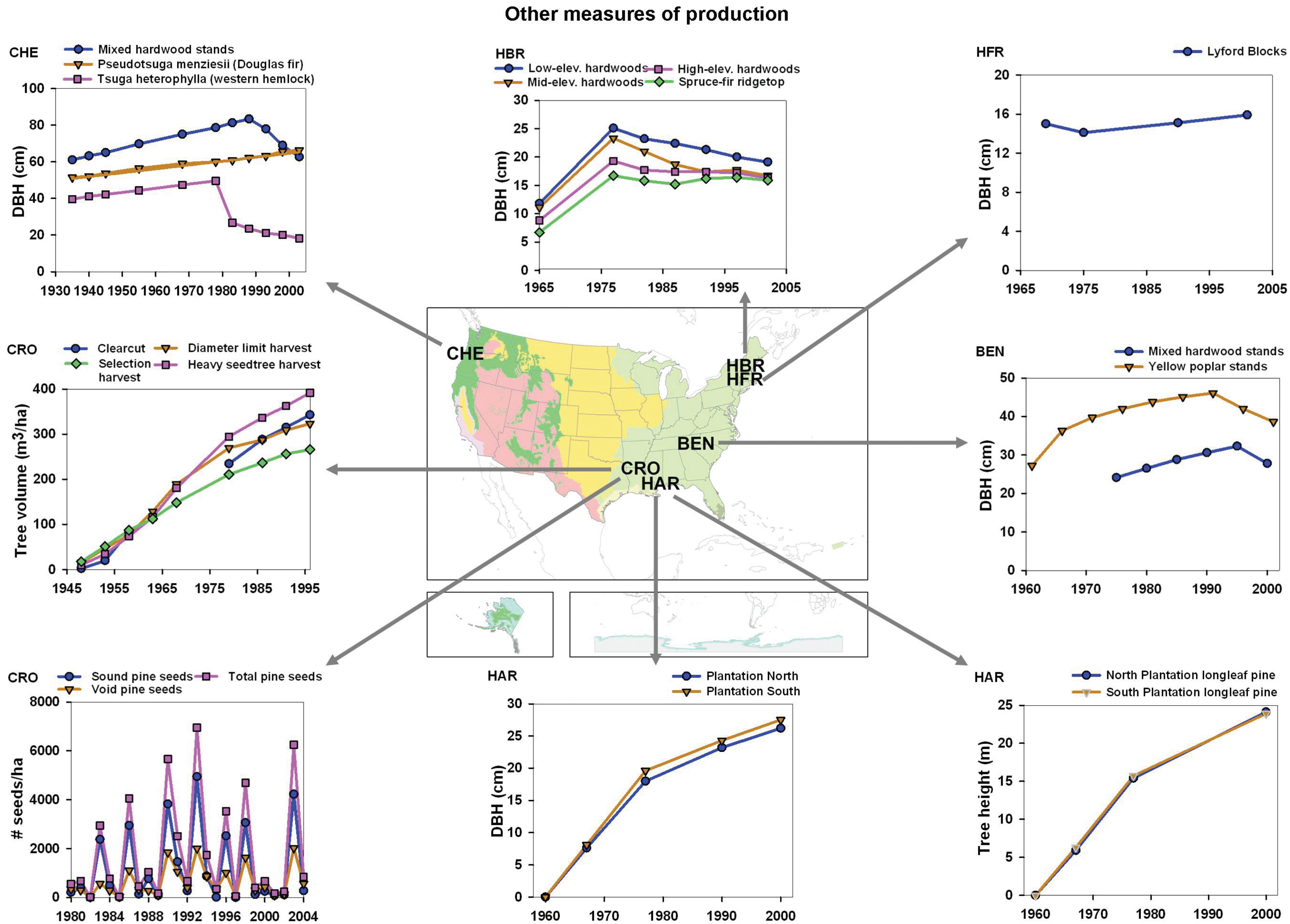

Figure 14-3. Other measures of terrestrial productivity for six forest sites (BEN, CHE, CRO, HAR, HBR, and HFR). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slope is CHE (1). Original data from Internet home pages (see table 1-1). Synthesized data from http://www.ecotrends.info.

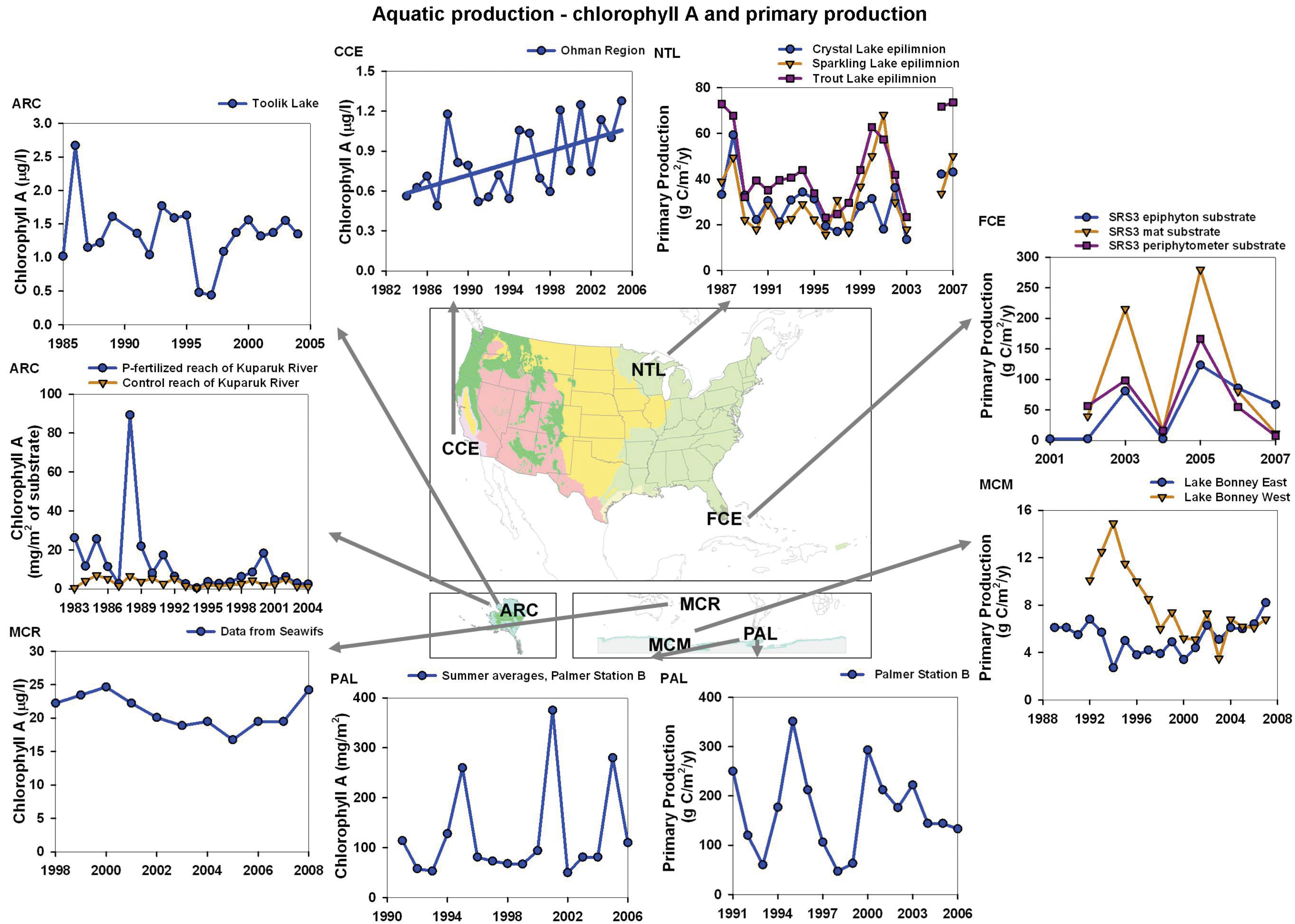

Figure 14-4. Aquatic productivity, either as chlorophyll A (µg/L or mg/m²) or primary production (g C/m²/y) for seven sites (ARC, CCE, FCE, MCM, MCR, NTL, and PAL). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slope is CCE (0.02). Original data from Internet home pages (see table 1-1). Synthesized data from http://www.ecotrends.info.

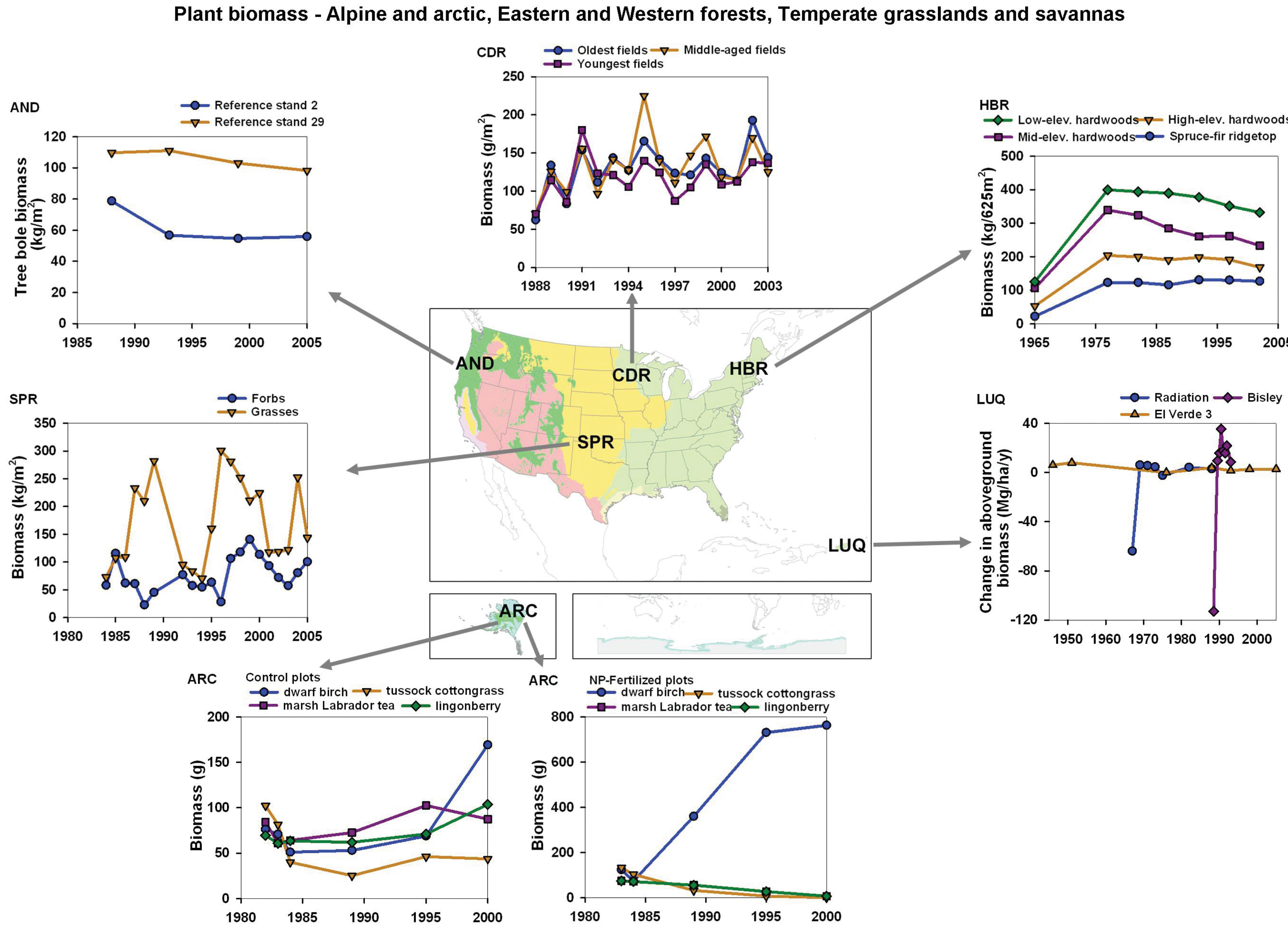

Figure 14-5. Plant biomass for alpine/arctic (ARC), forest (AND and HBR), and grassland (CDR and SPR) sites. See appendix 19 for the taxon/taxa specific to each site. A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. Original data from Internet home pages (see table 1-1). Synthesized data from http://www.ecotrends.info.

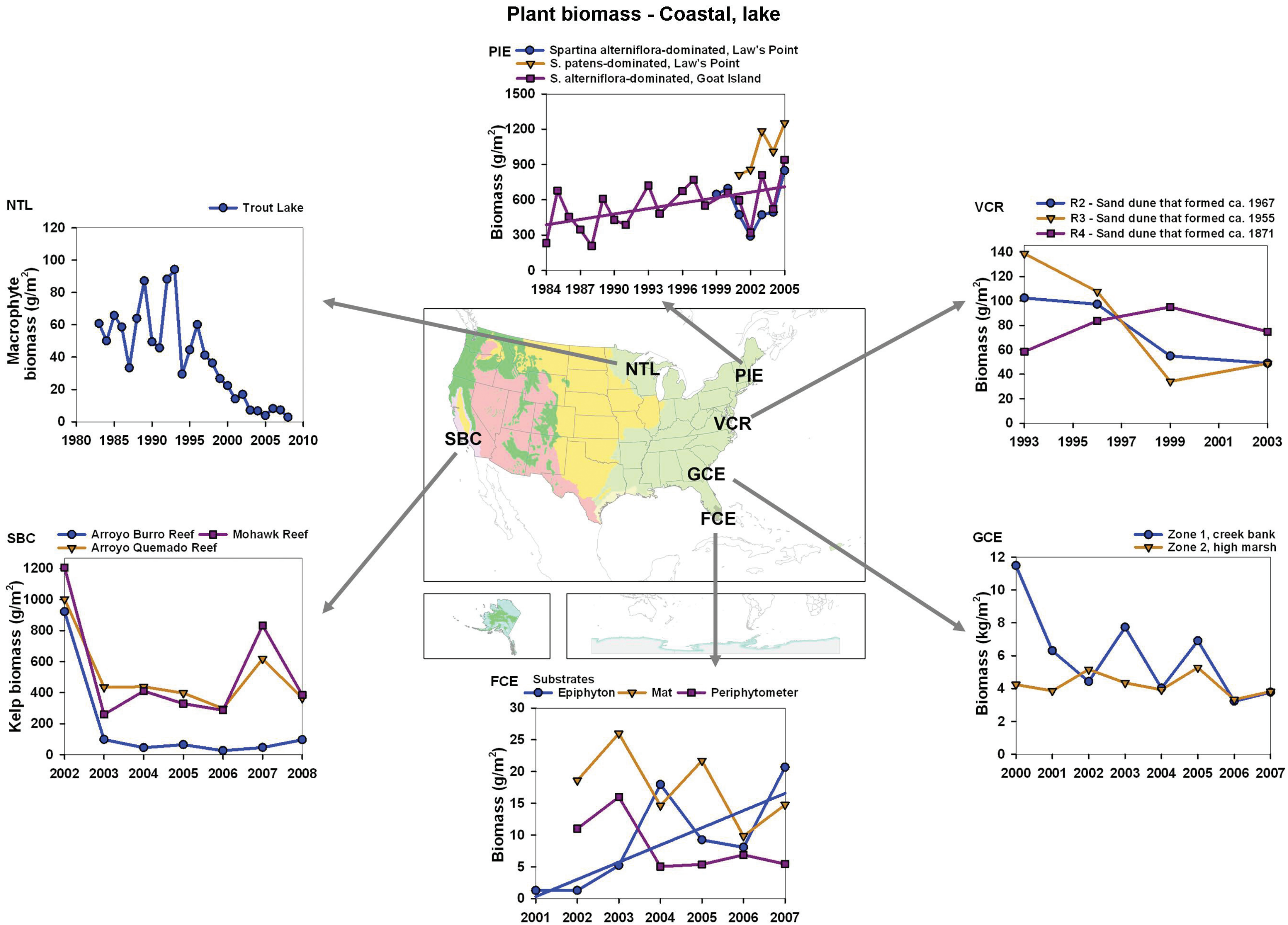

Figure 14-6. Plant biomass (and algae, if noted) for coastal and lake sites (FCE, GCE, NTL, PIE, SBC, and VCR). See appendix 19 for the taxon/taxa specific to each site. A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are FCE (2.7) and PIE (15). Original data from Internet home pages (see table 1-1). Synthesized data from http://www.ecotrends.info.

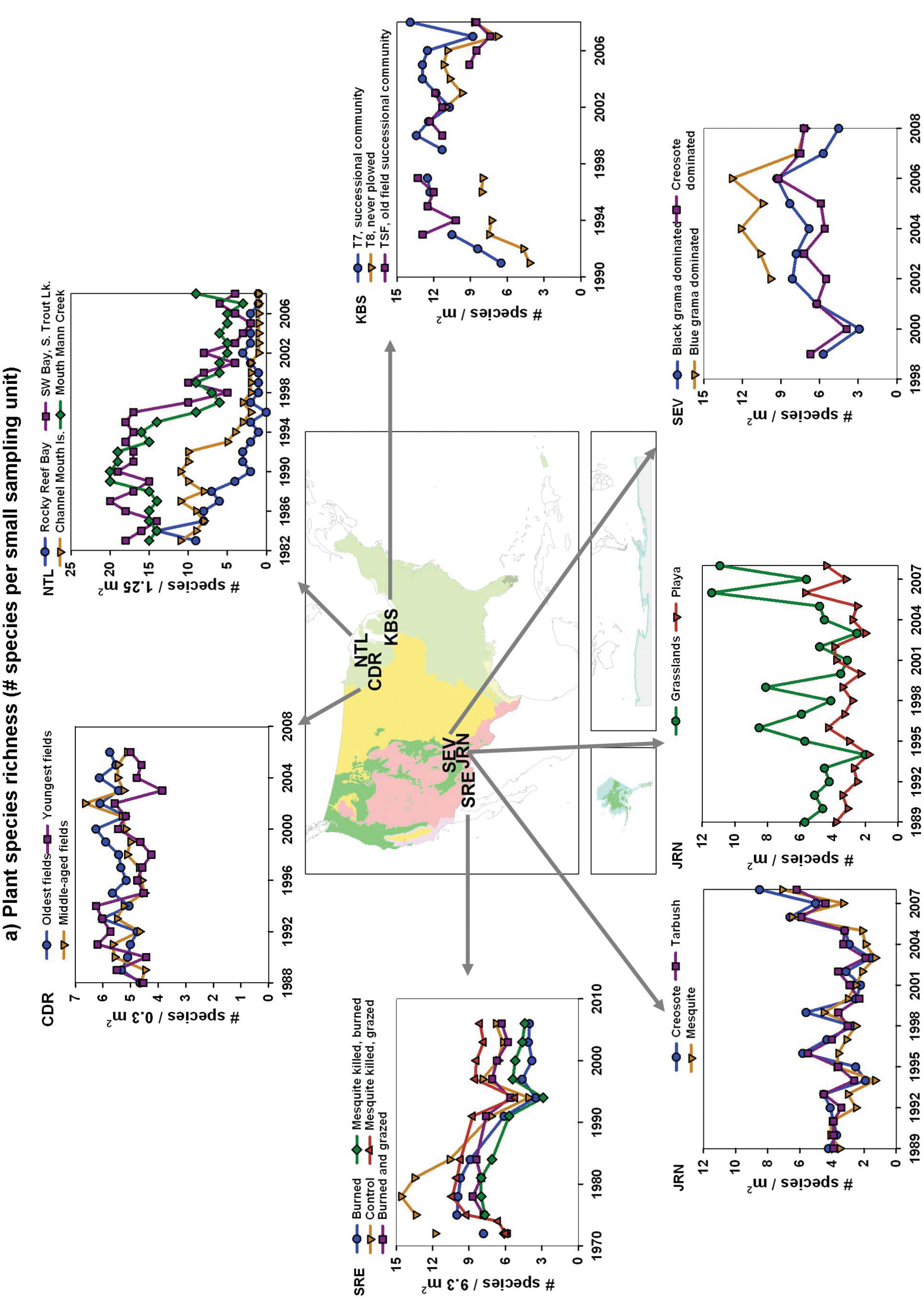

Figure 14-7 continued next page.

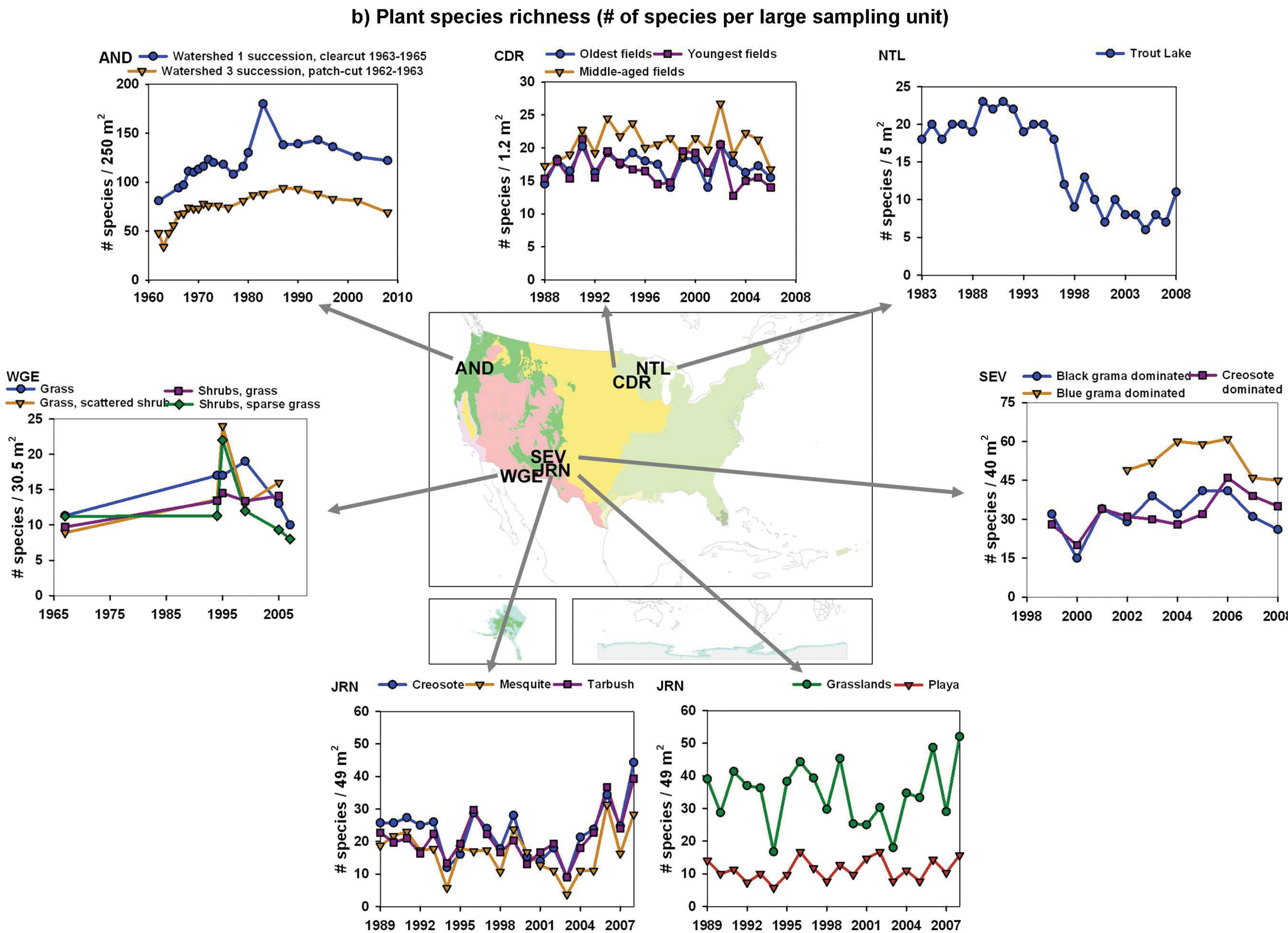

Figure 14-7. Plant species richness for eight sites (AND, CDR, JRN, KBS, NTL, SEV, SRE, and WGE): (a) at small sampling units (0.3-9.3 m²) and (b) at large sampling units (1.2-250 m²). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. Original data from Internet home pages (see table 1-1). Synthesized data from http://www.ecotrends.info.

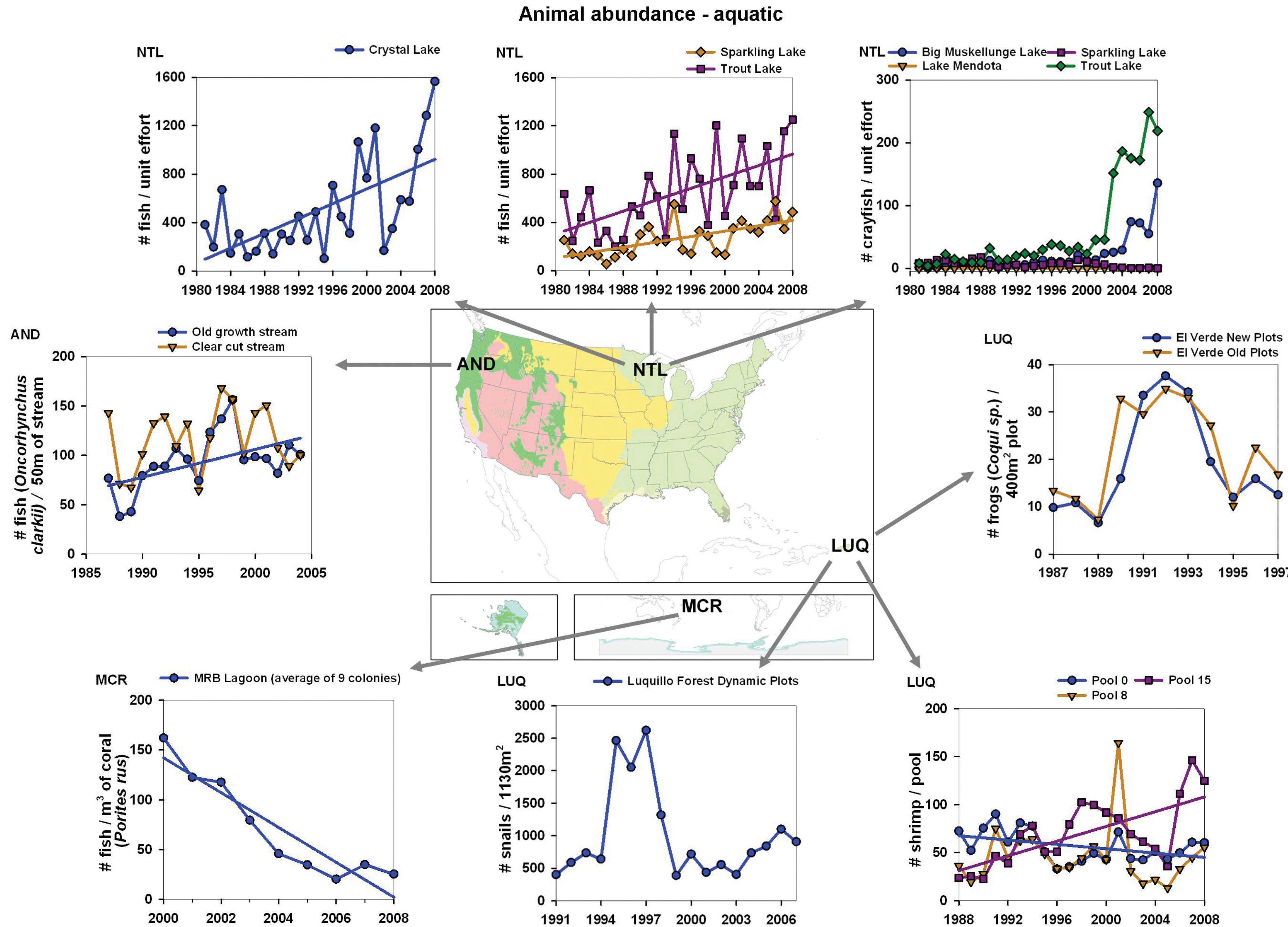

Figure 14-8. Abundance of aquatic animals at four sites (AND, LUQ, MCR, and NTL). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are AND (2), LUQ (-1, 4), MCR (-17), and NTL (11, 24, 31). Original data from Internet home pages (see table 1-1). Synthesized data from http://www.ecotrends.info.

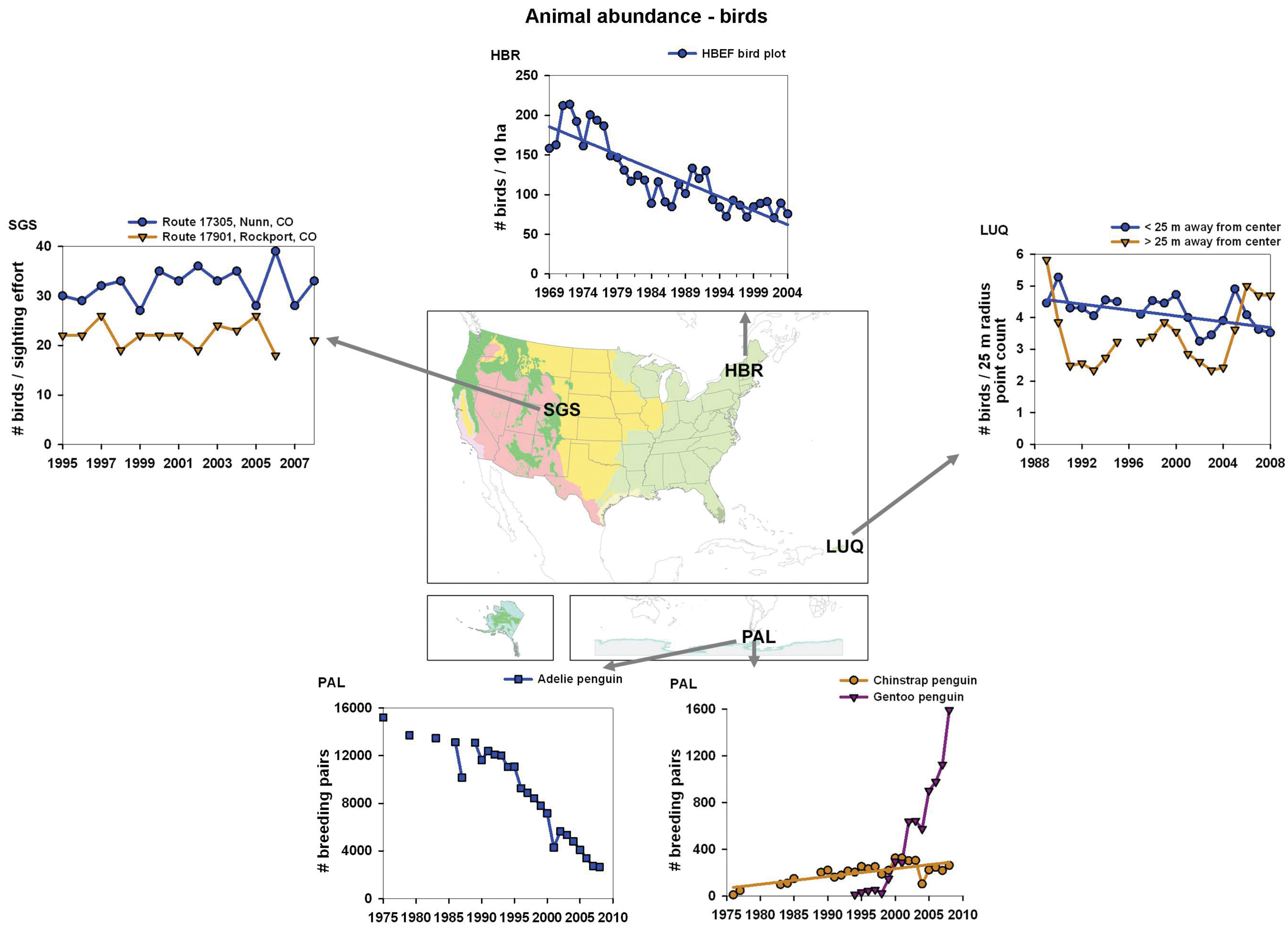

Figure 14-9. Abundance of birds at four sites (HBR, LUQ, PAL, and SGS,). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are HBR (-3.53), LUQ (-0.05), and PAL (6.70). Original data from Internet home pages (see table 1-1). Synthesized data from http://www.ecotrends.info.

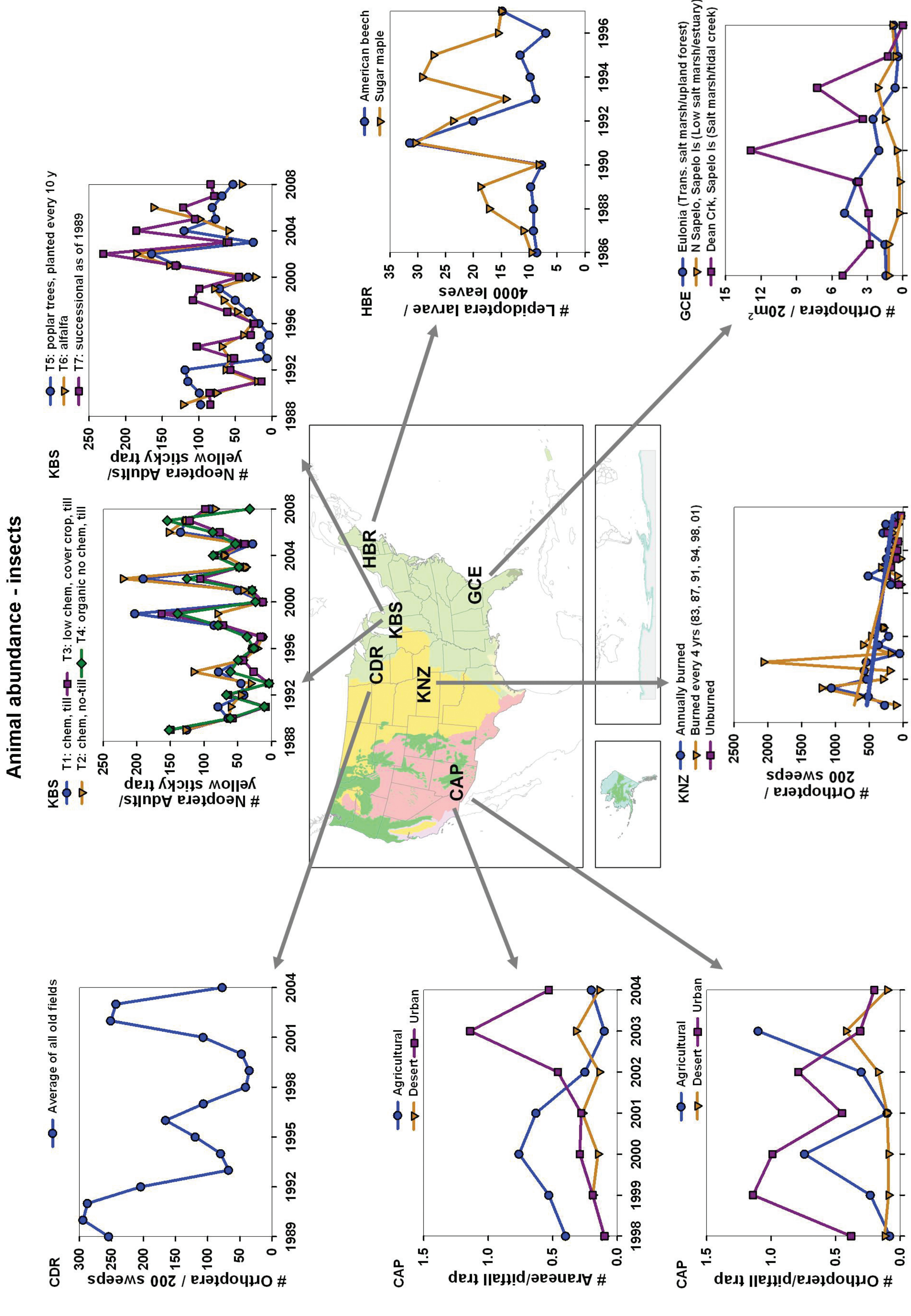

Figure 14-10. Abundance of insects at six sites (CAP, CDR, GCE, HBR, KBS, and KNZ). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are KNZ (-18, -32). Original data from Internet home pages (see table 1-1). Synthesized data from http://www.ecotrends.info.

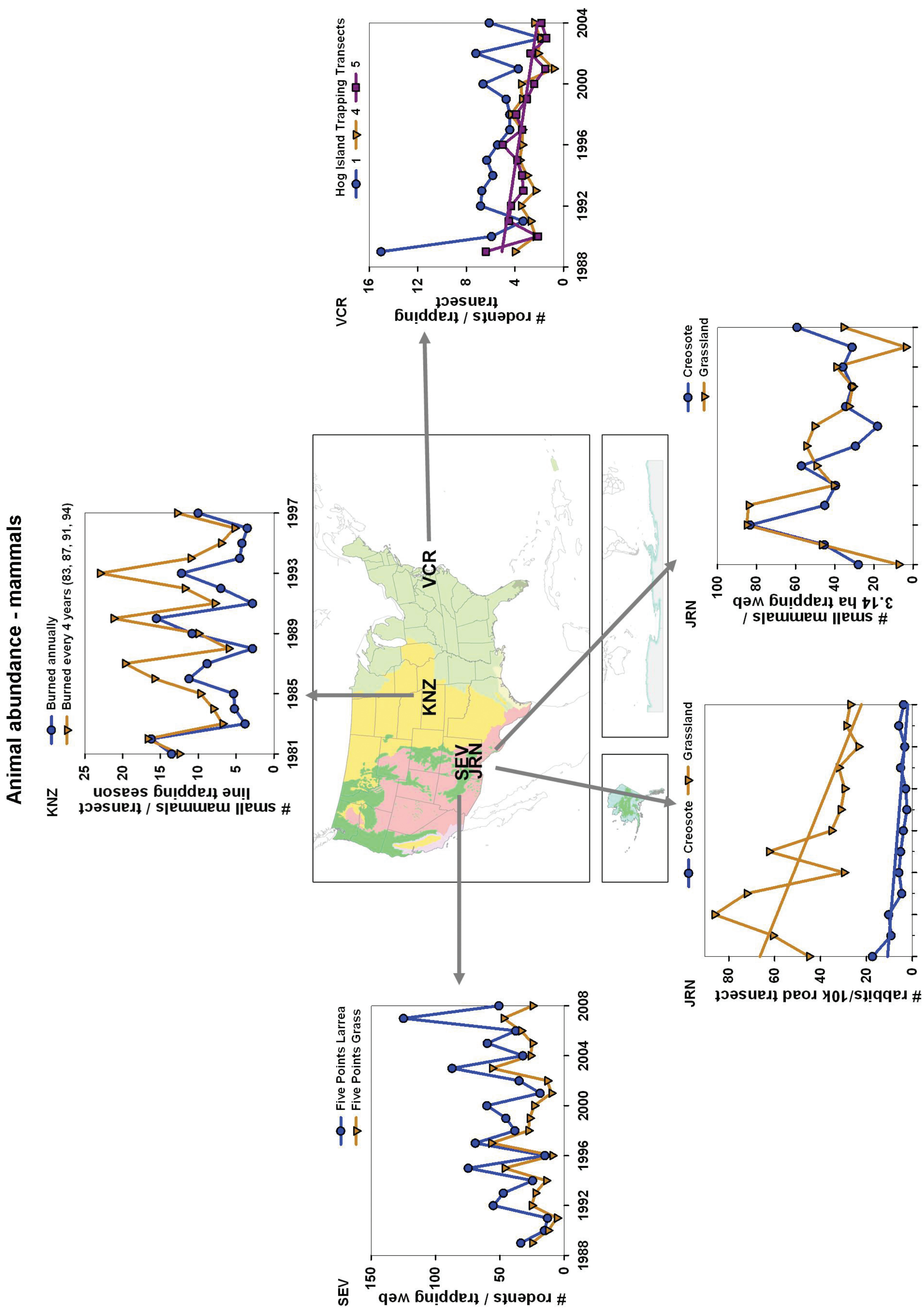

Figure 14-11. Abundance of mammals at four sites (JRN, KNZ, SEV, and VCR). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are JRN (-0.7, -3.7) and VCR (-0.2). Original data from Internet home pages (see table 1-1). Synthesized data from http://www.ecotrends.info.

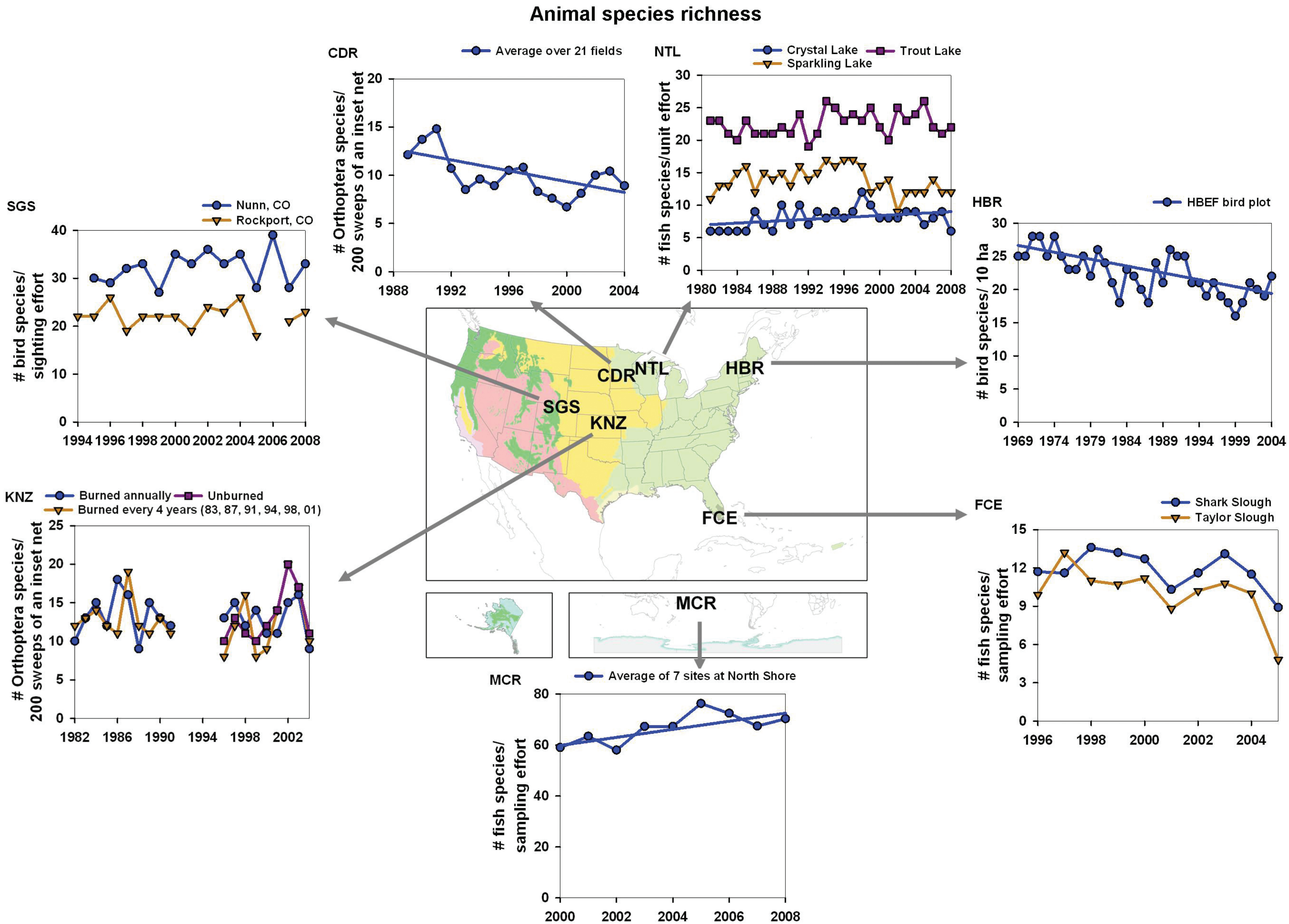

Figure 14-12. Animal species richness at seven sites (CDR, FCE, HBR, KNZ, MCR, NTL, and SGS). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are CDR (-0.28), HBR (-0.21), MCR (1.55), and NTL (0.07). Original data from Internet home pages (see table 1-1). Synthesized data from http://www.ecotrends.info.

Chapter 15

Management and Policy Implications of Cross- and Within-Site Long-Term Studies

K.M. Havstad and J.R. Brown

Management is defined as a set of processes that guide and evaluate actions required to implement a program. In the management of natural resources, it is understood that these processes are guided not only by science, but also by experiences learned by or conveyed to a resource manager over time. We recognize that information based on scientific studies and available through the peer-reviewed literature is often lacking or inadequate to address many of today's complex resource management issues.

Fortunately, long-term datasets are now becoming available that can provide useful information with application to natural resource management and policies. For example, climate, and particularly the occurrence of long-term drought, is a major driver of ecosystem dynamics across the United States. Long-term data provide a basis for evaluating not only the likelihood of drought, but resilience of drought within managed landscapes. Drought records, such as annual Palmer Drought Severity Indices (PDSI; figure15-1), provide these utilities to managers of both public and privately held natural resources. To illustrate, the historical record of PDSI for southern New Mexico (figure 15-1; JRN ARS-LTER) informs managers that over 75 percent of the years during this 50-year period were recorded droughts and that the drought of 1951-1956 was the most severe of its time. Management actions based on resource inputs, such as reseeding native grasses, implemented during this period would likely be failures, and the interpretation of their usefulness needs to be judged within this context of perpetual drought.

Another driver that strongly influences resource management is the increasing human population and the increased landscape fragmentation accompanying these population increases. Census data collected since the late 18th century show an increase in population density across the continental United States that can seriously impact natural resources and their management (figure 15-2). These long-term data reflect the heterogeneous nature of population dynamics across the country. For example, in the late 20th century, growing population demands on water resources in the Southwestern United States are quite evident (Jackson et al. 2001). Conversely, decreases in human population densities across rural counties of the Central Plains will likely result in a loss of knowledge and experience in natural resource management.

These examples illustrate the value of long-term data beyond their contribution to our understanding of important ecological processes. Specifically, the value of long-term data to management of natural resources includes a basis for the development of—

- conservation practices which have direct application to natural resource management,
- policies and programs that can be instrumental in guiding that management, and
- adaptive strategies required to contend with both the spatial and temporal heterogeneity that are characteristic of natural resources and managed landscapes.

These values emerge from analyses of long-term data based on two key attributes: our ability to examine data retrospectively to identify temporal and spatial sensitivities and our ability to build those historical perspectives into predictive models with which we can objectively evaluate potential future scenarios. Both attributes provide the needed perspectives to manage our natural resources and to adapt our management practices to conserve those resources and mitigate the effects of our actions.

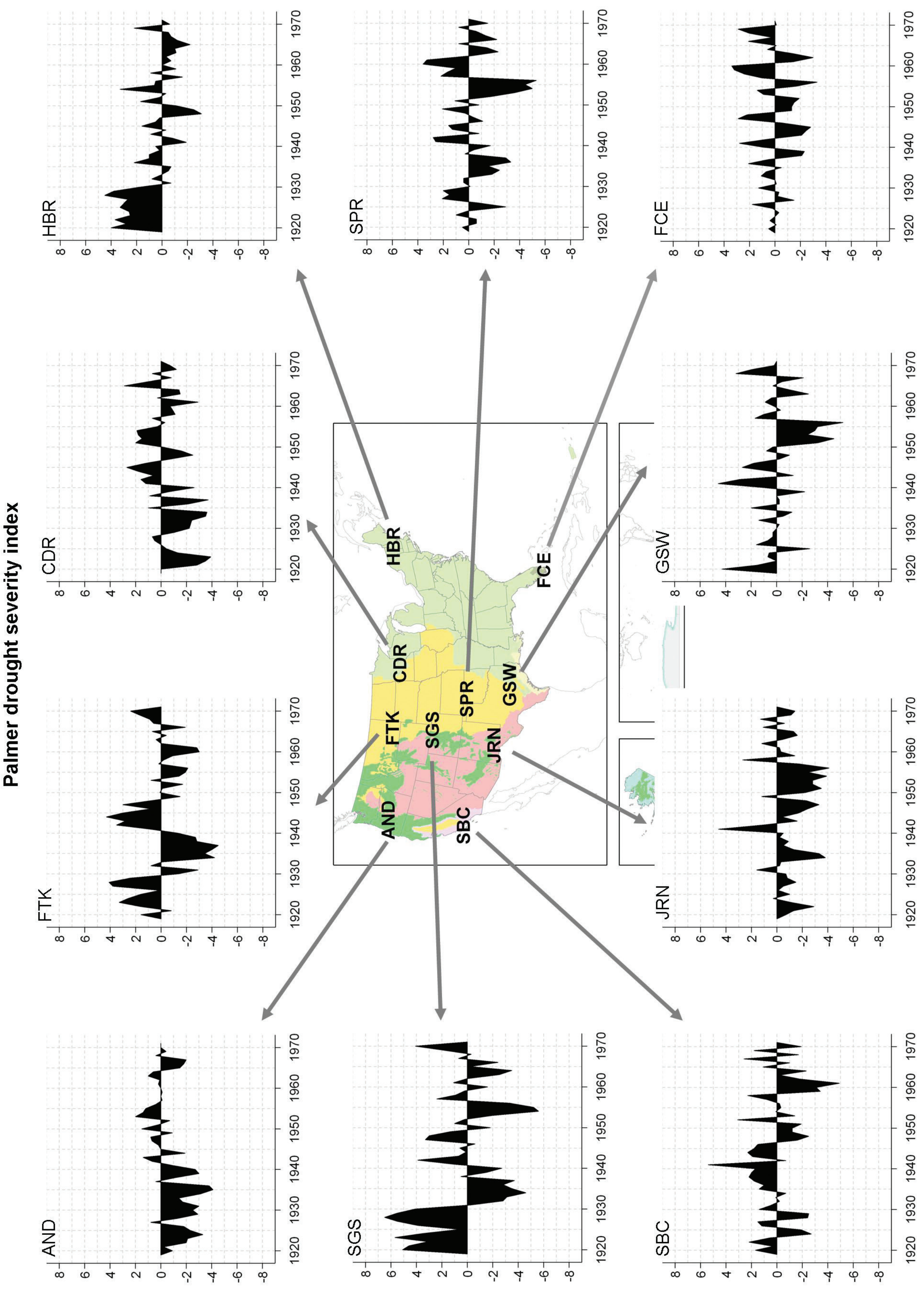

Figure 15-1. Fifty years of annual Palmer Drought Severity Indices for 10 key locations across the continental United States. Original data from http://www.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

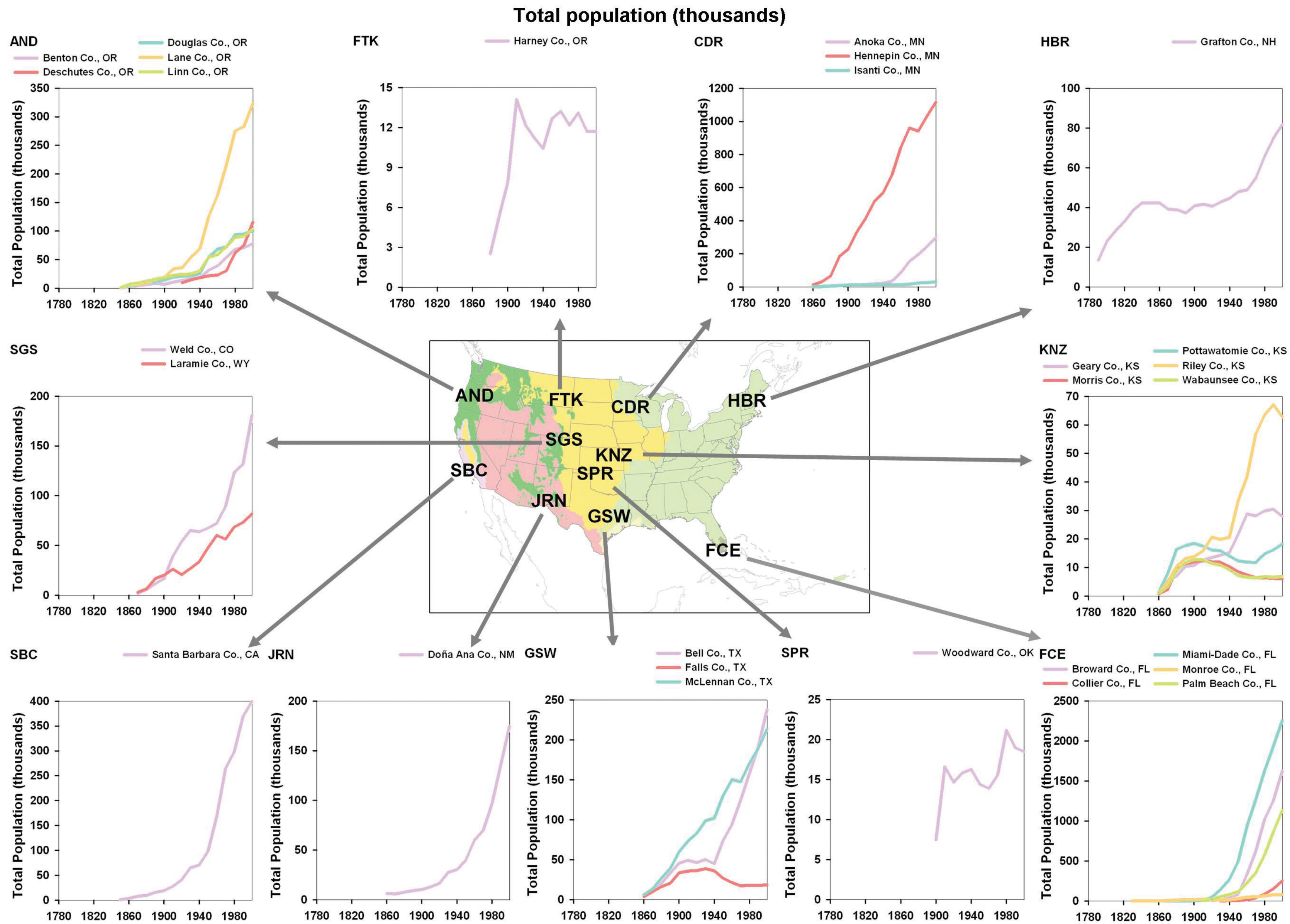

Figure 15-2. Long-term census data for 10 key locations across the continental United States. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

Historical Perspectives

Long-term data provide three important perspectives that are useful in management of natural resources. First, we are able to quantify temporal dynamics characteristic of natural systems. For example, in the St. Lawrence River watershed of Canada, 100 years of agricultural census data have allowed calculation of phosphorus accumulations in soils within that large basin (MacDonald and Bennett 2009). These long-term data document the periodic pulses that characterize soil phosphorus dynamics over decades and provide a basis for development of management strategies to contend with environmental issues associated with phosphorus accumulation, such as eutrophication.

Long-term data on soil nitrogen and carbon cycles in response to climatic drivers in the Hubbard Brook Ecosystem Study in New Hampshire provide a basis for modeling ecosystem responses to key environmental factors, such as temperature and snow levels, and to possible future climate scenarios (Groffman et al. 2009). These models also illustrate different responses of carbon and nitrogen to future changes in temperature and soil moisture and provide a basis for forest management policy decisions.

Data collected for nearly a century in south-central New Mexico have been analyzed to identify the climatic variables and rangeland management factors that contribute to vegetation dynamics over time (Yao et al. 2006). Repeat photos beginning in 1937 have been analyzed to characterize vegetation dynamics in this desert system (figure 15-3). Collection of these types of data and their subsequent analyses provide insight into the influences of extreme climatic events and provide a basis for projecting responses under future climatic scenarios. The data illustrate the episodic nature of invasive species dynamics and changes that often respond to co-occurrence of disturbance factors, such as overgrazing by livestock during multiyear droughts (Fredrickson et al. 1998). These data have informed grazing management practices and policies at the State and regional scale.

Forty years of data on vegetation responses to landscape modifications in an Atlantic forest showed a time lag in responses of numerous species to those modifications (Metzger et al. 2009). These long-term data demonstrate the importance of landscape history in affecting species presence and diversity within a region and the effects of species attributes on important aspects of ecosystem function (such as carbon storage) and resilience.

Long-term data also provide opportunities to evaluate responses to management actions over time. In another example drawn from southern New Mexico, we have been able to track vegetation responses over time to specific vegetation management practices (figure 15-4). In numerous other examples across the United States, historical treatment areas can also be evaluated from either ground-based records or from archived aerial photography.

Similar experiments conducted on several sites across the continent can provide insights into the effects of management on ecological processes. For example, rangeland grazing management practices have been studied on numerous sites across the Western United States throughout much of the 20th century. Recent analyses from these studies show that two common types of grazing systems showed similar responses in plant production for 89 percent of studies: 36 percent of studies showed greater animal production per head for continuous grazing than for rotational grazing, while 57 percent of studies showed no difference between grazing systems (figure 15-5a) (Briske et al. 2008). Studies were conducted at locations across the Western United States (figure 15-5b).

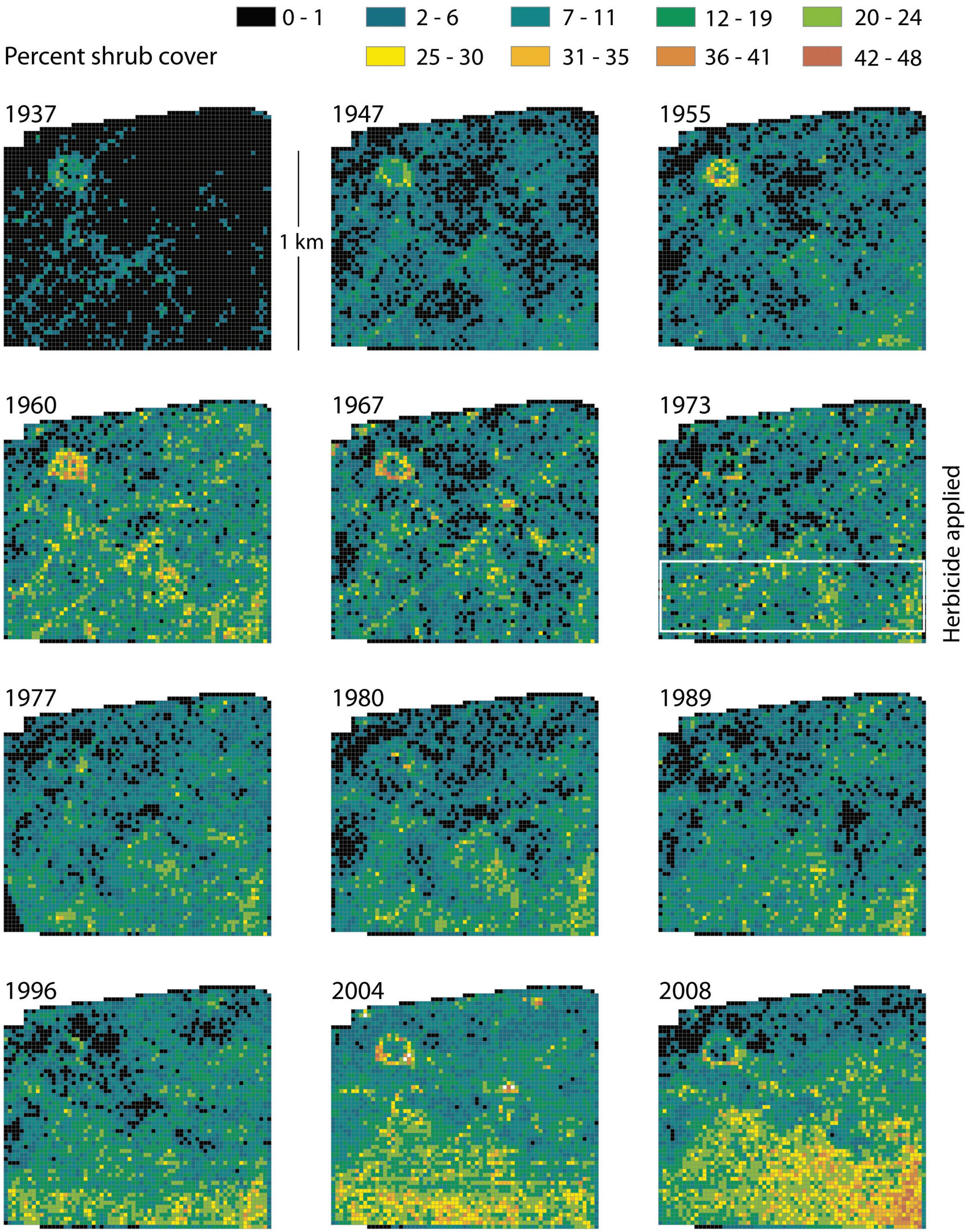

Figure 15-3. Repeat time series of aerial photographs over a 71-year period in southern New Mexico illustrating a variable increase in percentage of shrub cover through time as a result of extreme climatic events. Shrubs increased dramatically between 1937 and 1947 and again between 1996 and 2008. (D. Browning, unpublished data.)

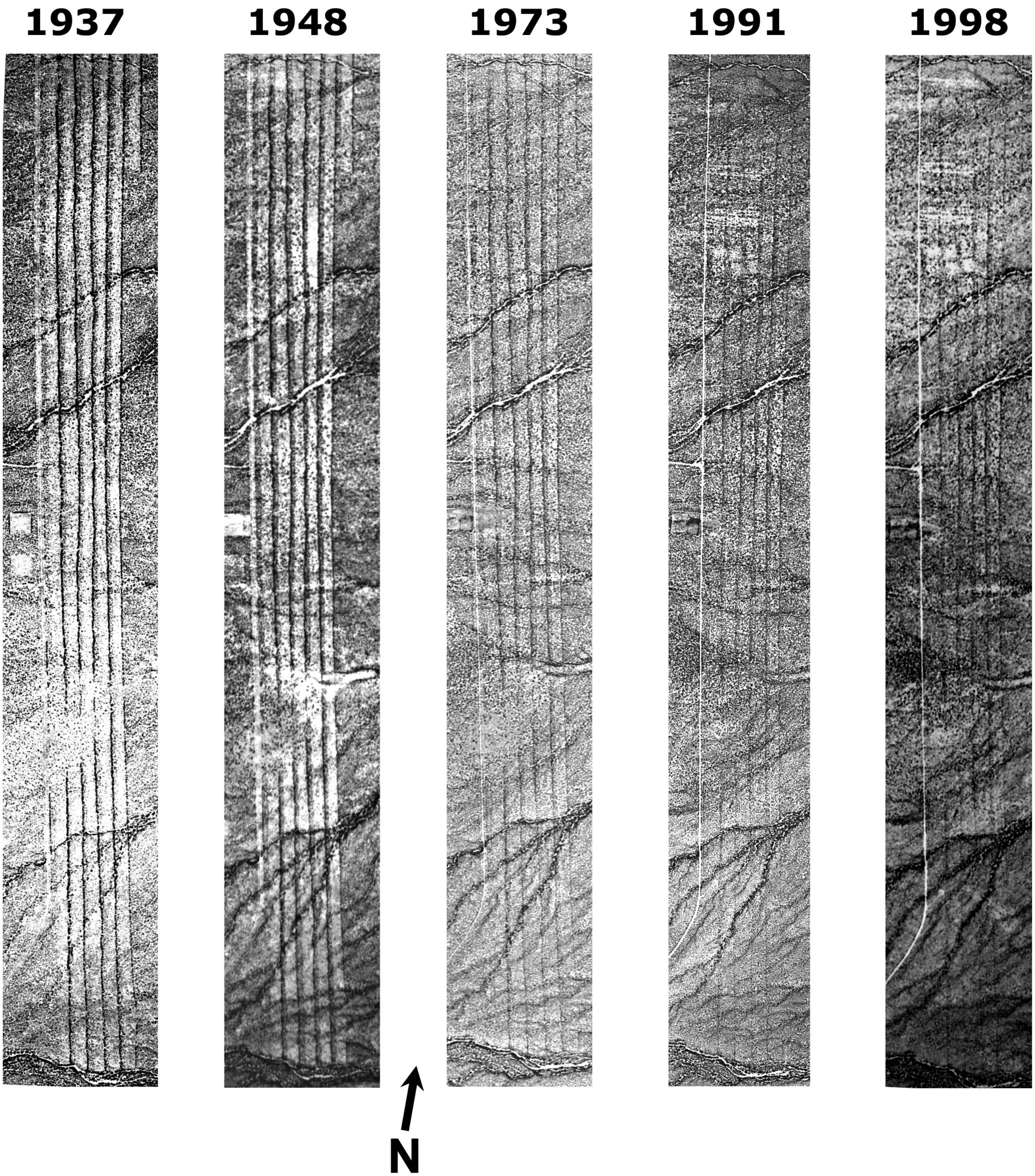

Figure 15-4. Temporal sequence over a 61-year period of alternating grubbed (shrubs physically removed at the ground-surface level; light-colored strips) and control areas (dark strips) in a predominantly creosotebush-dominated shrubland in southern New Mexico. Original grubbing was performed in 1936. Aerial photos were taken from flights in 1937, 1948, 1973, 1991, and 1998 (Rango and Havstad 2003). Reprinted with permission from Cambridge University Press.

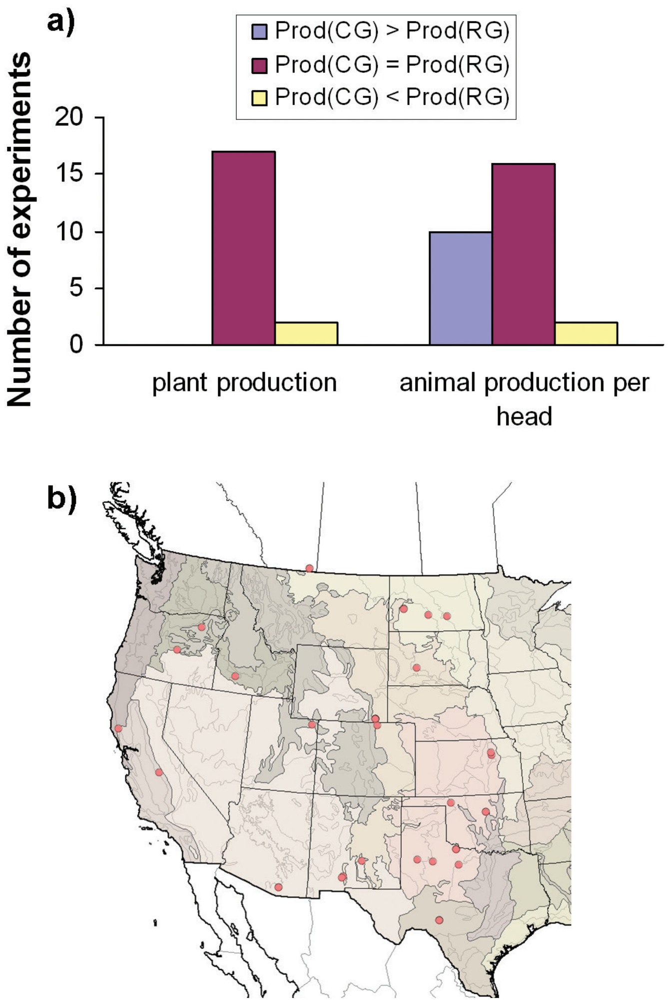

Figure 15-5. (a) Synthesis of research results from long-term studies of the response of plant and animal production to two common types of grazing systems: continuous grazing (CG) and rotational grazing (RG). When stocking rates were similar, 89 percent of the studies showed no difference in plant production between grazing systems, 36 percent of the studies showed greater animal production per head for CG than for RG, and 57 percent showed no difference between CG and RG. Redrawn from Briske et al. 2008. (b) Studies were conducted at locations (represented by red dots) across the Western United States. Map by Shawn Salley.

Predictions

Another important application of long-term, cross-site data collection is to develop and run mathematical models of ecosystem behavior, especially to predict responses of ecosystem services (such as water quality, carbon flux) to changes in climate, land use, and management. As the solutions to environmental issues become more contentious, the effects of human activities become more extensive in both space and time. In addition, the cost of conducting long-term, multisite field experiments increases. A reliable set of predictive models that can be used to estimate the effects of a variety of climatic and management scenarios are critical to informed decisionmaking and effective communication.

Examples exist of the application of complex models to integrate a small set of land management options and climate scenarios for the purpose of predicting a limited range of ecological and socioeconomic response variables (an example is the USGS's Land Carbon Project [USGS 2009]). However, consistency and transparency remain critical problems. The foundation for improving modeling approaches is ready access to data from well-designed, replicated experiments that can encompass the ecological, social, and economic questions of interest. Few experiments are currently designed, conducted, and analyzed with a focus on improving the performance of a mathematical model. Experiments often lack the range of treatments necessary to confidently predict beyond a fairly narrow set of circumstances. As a result, the use of some popular models to predict ecosystem response is ill advised (Brown et al. 2010).

Traditional comparative treatment experiments should be continued in order to more efficiently develop existing and new models. Improving the performance of models with the use of long-term data from multiple locations will remain a challenge and will require serious thought and commitment of resources to ensure that the sometimes conflicting goals of hypothesis testing and model development are met. However, the value that long-term, multisite data have already contributed to the use of mathematical models that predict ecosystem behavior and that guide policy and land management decisions demands that serious efforts be mounted to organize existing data and to cost-effectively collect new information.

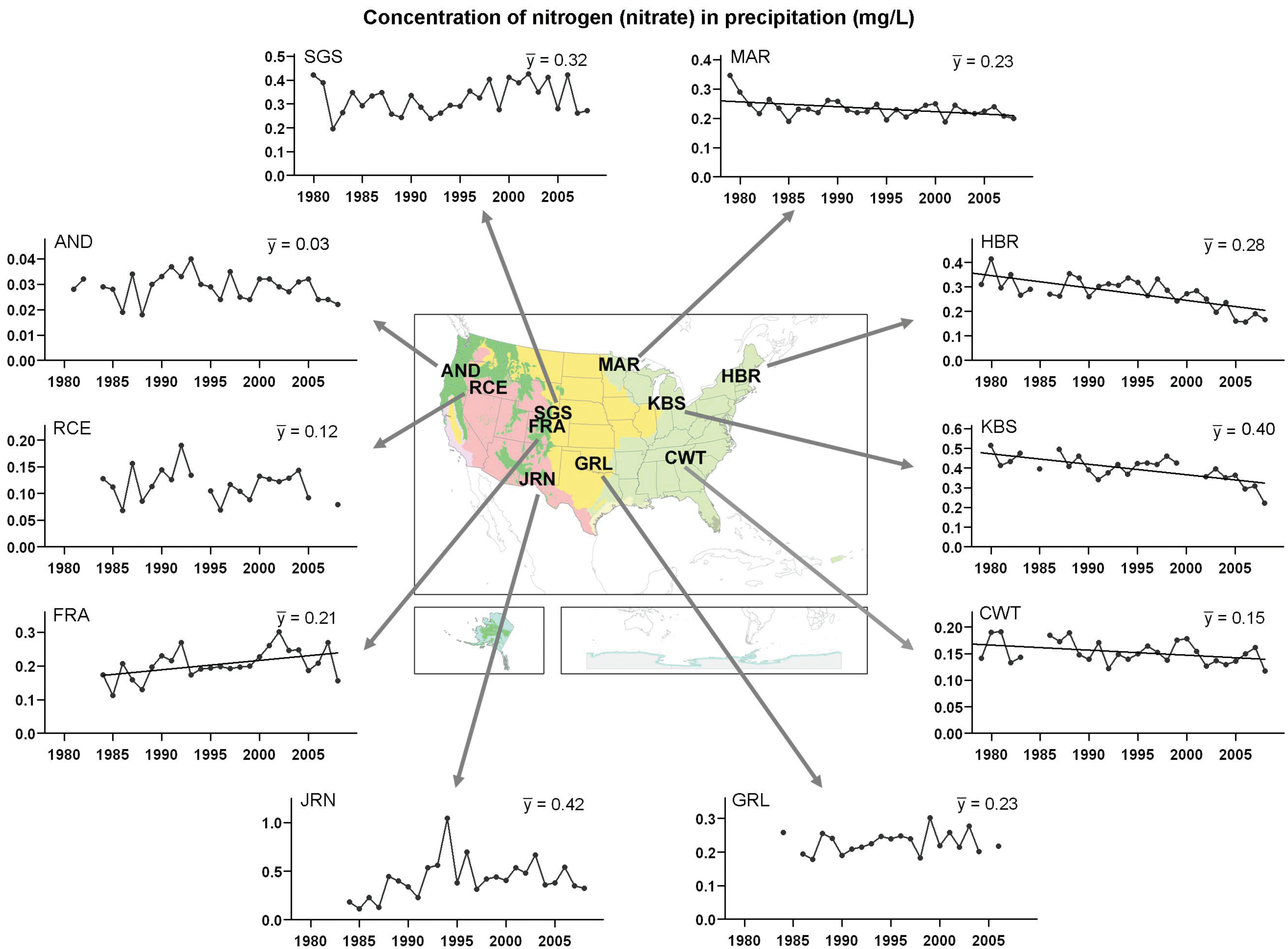

Figure 15-6. Nitrate concentrations recorded in precipitation (mg/L) over a 25-year period following Federal clean air policies enacted in the 1970s. Original data from http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

Summary

Long-term data and their collection at specific sites across the United States have provided three distinct, but complementary, values to management of natural resources.

First, these data provide an opportunity to understand the temporal and spatial variability of many ecological patterns and processes. This value is important because many management actions, such as prescribed burning or reseeding of degraded land, incorporate key ecological processes and are sensitive to both location and time. For example, the timing of synergistic environmental conditions, such as periods of dryness for prescribed fires or periods of subsequent moisture for reseeding practices, is an important constraint on the success or failure of management actions.

Conversely, most management actions are highly dependent on site features. It is commonly understood that no single management practice will work in all locations at all times. Without long-term data across numerous sites, we cannot identify this array of temporal and spatial sensitivities nor develop data-based guidelines to direct the appropriate timing and application of management practices.

Second, long-term data provide the opportunity to evaluate policies and programs that have been implemented for resource conservation. Often, policies are developed and enacted with incomplete knowledge of ecological ramifications. The ability to evaluate environmental responses after policy implementation provides the data necessary to validate policies or may lead to their subsequent revision. Of additional importance is the value of long-term data in assessing and monitoring ecological responses to implemented policies. For example, nitrate concentrations in precipitation collected at locations across the United States reflect the positive effects of federally mandated clean air policies enacted in the 1970s in reducing nitrate concentrations in the industrialized upper Midwest and the Eastern United States (figure 15-6). Areas of the less industrialized West and Southwest reflect negligible effect of these policies, as would be anticipated.

In another example, a key technology for management of rangeland resources is an ecologically based system for delineating landscapes into units of similar vegetation potential that are expected to respond similarly to a management practice. The principal provider of this technology since the mid 20th century is USDA Natural Resources Conservation Service (NRCS). For decades, this technology was described as "range sites," where the condition of a site is characterized by its linear departure from a potential determined by the combination of climate and soil properties. This technology was based on an assumption that state changes are reversible and that the potential of a site is consistent over time. In the 1990s, NRCS revised this management technology in an effort to incorporate an understanding drawn from long-term data which state that changes may be irreversible and that site potentials are not permanent over time (Bestelmeyer et al. 2003). The new technology, known as "ecological sites," represents an improved tool that is more firmly rooted in a data-based understanding of the ecological dynamics of arid and semiarid ecosystems (Bestelmeyer et al. 2009).

Third, long-term data collection provides the opportunity for clients, partners, and stakeholders to be engaged in scientific processes. Often, long-term study sites, such as those that contribute to EcoTrends, are platforms for cooperative and collaborative activities with users of the information. These interactions create opportunities not only for technology and information transfers but for users to inform the science and its research directions. This kind of involvement increases the likelihood for research to be conducted that has impact and enhances the utility of long-term data.

It would be difficult, if not impossible, to adequately estimate the economic cost of developing today the network of sites and their long-term data sets that exist across the continent. As a reference point, the National Science Foundation has committed over $300 million to develop the soon-to-be-established National Ecological Observation Network (NEON) at 60 locations across the country. This network will be a sensor- and tower-based system; and though highly advanced scientifically and technologically, NEON is not as expansive as the land-based network of research sites currently in existence that form the basis for data in this book. The investment required today to develop the long-term data system currently in place would likely require many billions of dollars, if sites could even be selected and secured from existing land uses. Fortunately, these sites and data sets are in place, and their value to management of our natural resources is both evident and real.

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Chapter 16

Recommendations for Data Accessibility

C.M. Laney, K.S. Baker, D.P.C. Peters, and K.W. Ramsey

The EcoTrends Project was established to aid researchers and others interested in synthetic studies of long-term, continental-scale and national-level patterns in environmental drivers and ecological responses. Hundreds of standardized, documented datasets from many sites and scientific fields were synthesized to meet this goal. Generating comparative data at many sites across several organizational networks and finding novel solutions to technical, organizational, and communication challenges required ongoing collaborative work with all project participants, including researchers and information managers.

The lessons learned from this collaborative effort contributed to our understanding of contemporary ecological information management (that is, the management of digital ecological data via multifaceted, interdependent arrangements and systems). Drawing on these lessons learned by EcoTrends participants—project leaders, researchers, and network- and site-level information managers—we present 10 recommendations for site-level information management and for future synthesis projects. These recommendations for supporting synthesis projects are related to three broad categories:

- Data management and products
- Project design
- Information environments

Challenges

The collection, management, and sharing of ecological data are rapidly changing because of escalating advances in technology and in knowledge-sharing. Advances in automated, continuous collection of data from sensors are increasing the number of methods available to observe and measure the environment. These technologies and methods can generate data that span a wide range of spatial and temporal scales (see Porter et al. 2005, Collins et al. 2006, Benson et al. 2010 as examples). Management of data has evolved along with statistical software and database technologies. For example, quality checking of data for errors in values and formats was previously conducted manually by researchers or technicians but is now often performed using automated statistical software (for example, Michener and Brunt 2000). Data that were once stored in simple spreadsheets are now often stored in more complex relational databases. The sharing of data and knowledge has increased as more research sites post links to their data on web pages or make the data available via new web services. To aid in the sharing of data, data practices, policies, and documentation standards have been and continue to be developed among research communities (for example, Karasti and Baker 2008, Porter 2010, Vanderbilt et al. 2010).

Large synthetic studies of diverse ecological data have been greatly facilitated in recent years by advances in data collection, management, and sharing, which is exciting for the research community, but these new projects also pose new challenges. Comparing large amounts of data across diverse ecosystems can aid in understanding of ecological processes and the effectiveness of new research methodologies. When such analyses lead to new understandings about ecology and ecological data, the lessons learned can inform the next round of data collection, processing, analysis, and documentation. Thus, large synthesis projects have been increasingly popular over the past few decades (for example, Riera et al. 2006, Moran et al. 2008). However, new challenges have appeared with each large-scale project. Here, we describe the primary 10 challenges that the EcoTrends Project faced, grouping them into three categories.

The first category addresses data management and products. Ideally, datasets would be easy to find online and to incorporate into a well-defined workflow for databasing and analysis. However, as the EcoTrends project illustrates, the task of finding and creating comparable datasets from disparate sources can be challenging because of several underappreciated impediments, including—

- difficulties in finding data,
- inadequate data and metadata standards,
- inaccurate or incomplete data and metadata content, and
- complex datasets.

Similar issues have been identified in other environmental science synthesis projects (for example, Benson et al. 2005, Jones et al. 2006, Michener et al. 2007, Baker and Chandler 2008).

The second category addresses synthesis project design. There are many ways to start, design, and implement a synthesis project, and it is important to begin with well-defined goals, knowledgeable and enthusiastic partners, and a well-informed sense of the challenges that may be faced throughout the project. Challenges in this category include—

- data heterogeneity and scaling issues,
- planning flexibility into project design, and
- making decisions on how to best design and implement a project and its requisite information infrastructure.

Finally, the third category addresses information environments to support synthesis. Challenges include—

- working with and developing environments in which information is effectively shared among participants,
- finding motivation to continue the project over time, and
- encouraging involvement of a large number of research sites.

Over the course of the EcoTrends project, participants accumulated a rich body of experience with data processes and collaborative data practices. While large datastreams and technology configurations have prompted a variety of large-scale program endeavors, the EcoTrends project is unique as a multisite, multinetwork activity involving ecological data that span biological, chemical, and physical realms. The project simultaneously informed development while coordinating site- and network-level information environments.

In the next section, we provide recommendations related to the challenges listed above. For each recommendation, we first provide specific examples of the challenges that EcoTrends faced, then the lessons that we learned, and then explain the recommendation that may help address the challenge in future projects. These recommendations are expected to resonate with researchers and information managers, who work together as a cohesive, integrated team at both research sites and in multisite comparative studies of ecological data.

Recommendations for Data, Metadata, and Derived Data Products

1. Make data easily accessible online to researchers.

Locating data for the EcoTrends Project was a time-intensive exercise. A small, but significant, portion of datasets were not stored online, but were submitted via email by individual researchers or information managers. Moreover, online long-term datasets were often difficult to find within extensive catalogs of datasets on the webpage for each research site. Occasionally, when a research site updated its webpage, the link to a dataset changed, and the dataset would have to be relocated by EcoTrends personnel. These challenges were met by contacting researchers and information managers at each research site in order to solicit data that were not online, locate data that were online but difficult to find, and find datasets when they had been moved.

We recommend that research sites be supported in developing practices and procedures to make high-quality, well-documented datasets publicly available online as soon as possible. For example, the Long Term Ecological Research (LTER) program data policy, based on guidelines from the National Science Foundation, states that data should be posted within 2 years of being collected, with a few exceptions. In addition, we recommend that each dataset be assigned locally a unique identifier code, or accession number, that does not change over time. This identifier would make it easier for a synthesis project to more easily find a dataset that has been moved. Dataset titles are often used as identifiers, but these titles are subject to change when datasets are reorganized or displayed at different Internet locations.

2. Implement and develop metadata standards at the site and community levels.

The metadata documentation format was highly variable between research sites. At some research sites, each researcher documented datasets in a format unique to his or her personal standards of completeness. Other sites maintained site-level standards, such as filling out specific fields in a text document. Data downloaded from national repositories usually adhered to the standards created or adopted by that particular repository. For example, metadata from the Climate and Hydrology Databases Project reports metadata for each dataset via a standardized form, the completeness of which varies between participating sites. The LTER sites (approximately half of the participating research sites), however, recently adopted a standard metadata protocol, the Ecological Metadata Language (EML). This specification documents datasets with information such as study location, data collection methods, data policies, and descriptions of data table elements. It also includes community-defined lists of terms, or ontologies, to aid standardization. With EML only recently adopted by the LTER community, many LTER datasets were not yet fully documented and many documentation best practices are still in development.

As a result, the metadata documents that EcoTrends personnel worked with were highly variable between datasets and were error-prone, such that time was spent trying to understand the data. In metadata documents, the locations where data collection took place were often missing. We found that a lack of variable naming conventions (for example, primary productivity may be labeled “primprod” in one table, and “PP” in another table—even within the same study) made data processing difficult. Species names were often recorded as codes in data tables, yet in many cases, the codes contained typographical errors or were not adequately documented in the metadata. In other cases, a lack of detail in the methods led to misinterpretations of how the data were collected. Discussions between the EcoTrends Project Office (EPO) and the lead researcher of the study became a necessary component in processing the data correctly.

EML was developed for a large, diverse community that intended to share data using standards that support consistent data packaging and routine update of datasets over time. The EcoTrends Project found that source datasets with EML documentation were often easier to understand and process than those without such documentation, thus the Project used EML to document every derived dataset that the project generated. These metadata documents contain information about the source dataset (including ownership and a link to the original metadata) and about the EcoTrends Project as well as definitions of the associated data table.

However, while the EcoTrends Project attempted to support the existing EML standards as thoroughly as possible, the resulting documents were incomplete. For example, the methods used to calculate the derived data from the source data are not included in the EML because a standard does not exist for this information. Derived datasets on the EcoTrends website may thus be misinterpreted, and the source data should be examined before proceeding with further analysis.

EcoTrends work brought the concept of derived data to the foreground. The issue of data misinterpretation was discussed with the broader community, prompting discussions about how to best accommodate this level of information within future EML schemas.

EML content standards are still in development, which means that a number of data comparability issues remain undefined. LTER information managers have been prominent advocates for improvement of EML, thereby benefiting the ecological research community. EcoTrends contributed to the development of site-level conventions and to the enactment of metadata standards by reporting documentation errors to site personnel. Specifically, benefits included prompting sites either to create EML for their historical data or to improve on what was available; to standardize attribute, unit, and taxonomic codes and names; to flesh out methods sections; and to provide stable Internet addresses (preferably with dataset accession numbers) for each dataset over time.

We recommend that research sites implement community-wide metadata standards, such as EML, and become involved in the process of refining existing standards and developing new local standards when community standards are not adequate for local research. Implementing local procedures with reference to community standards helps maintain data integrity at both the site and project levels. Standards that guide the documentation of a scientific study, its methodology, and the resulting data tables, can promote responsible sharing and use among researchers by clearly representing dataset origin and can make data more discoverable via online searches.

3. Develop and use standard data practices to create "clean" data.

Data lose their integrity if there are errors. We consider "clean" or quality-controlled data to be free of typographical or value errors and to be easily importable into a spreadsheet, a statistical program, or a database. In practice, there were frequent errors found in the source data that significantly hindered analysis and synthesis. For example, time-series data often had unexplained gaps. Occasionally, incorrect values, such as outliers or incorrectly labeled data (for example, mean temperature labeled as maximum temperature) were found by the EPO during the data processing or during data checking by site personnel. Outliers often existed in the data early in the study when techniques were new and the collection process had not been thoroughly tested. Where data and metadata gave no indication of poor quality or missing value assignment, problem data were inadvertently used in the initial analyses and corrected in the final analyses and graphs.

There are several plausible reasons for a lack of data integrity. Long-term data, assumed to be "clean" due to the long period of time that they have been maintained and their availability on the Internet, may actually suffer from neglect. Legacy data practices such as short and nondescriptive variable names or inadequate software tools for checking are often an issue. Alternatively, when delivery of data from site changes (for example, becomes updated, semiautomated, or automated), quality control, and other site-level analysis work may not be carried out or may not be adequately incorporated into the dataset.

By presenting source data in a recast form on a website, EcoTrends focused the attention of site participants on quality-checking of those datasets. Frequently during the site data checking process in 2008-2009, site personnel noticed erroneous data points in the annual summaries of their datasets, attributable to poor-quality primary data or to erroneous summarization of the data. Many source datasets and EcoTrends-derived datasets were corrected following discussions about data practices that occurred with individual researchers and at larger meetings.

While good data practices goes beyond the scope of this chapter, ***we recommend*** that sites act upon the developing resources available in the literature at the community level (Michener and Brunt 2000, Cook et al. 2001, Baca 2008, Borer et al. 2009) and the national or international level (NISO 2004, Van den Eynden et al. 2009). Data processing is an iterative exercise involving multiple facets, from sample analysis and measurement calibration to data analysis, quality control, statistical analysis, comparative study, and visualization. All of these activities can occur at both the site level, driven by scientific inquiry for a specific use of the data, and at the multisite or network level, driven by new, often synthetic uses of the data. Site-based analyses to scrutinize the data are needed before data can be used effectively by others. Development of good information-management practices must include ways to prevent misuse and/or misinterpretation of data.

4. Provide well-documented derived data for use by local and remote researchers.

In many cases, the source data were complex and difficult to process correctly due to unique collection and analysis methods. A goal of the EcoTrends Project is to create derived data products whose format is much simpler than the way the data were originally collected in order to ensure that a broad range of users can understand the data. The EPO, in consultation with the science advisory committee, aggregated data using methods commonly used by ecologists. Most of the time, these methods worked well. However, in some cases no matter how well documented and how cleanly represented in data tables, the complexity of the dataset was the main barrier to synthesis. Biotic datasets were particularly challenging, with numerous species and different kinds of measures. In many cases, the Project Office needed to discuss with the lead researcher the suitability of a dataset for a particular aggregation effort.

We recommend that research sites create and post online derived data products as long-term, signature datasets. These types of derived data products are not typically posted online, though they are often created and used for in-house analysis. There are two main reasons for our recommendation.

First, creating derived datasets provides a mechanism for performing regular checks on the integrity of the data, a procedure that helps ensure "clean data" (see recommendation 3). If the data are kept up-to-date in a standard format, then statistical programs can be written to periodically recheck the format of the data tables themselves, check the data table contents against what is recorded in the metadata, check for errors in the data, and produce visualizations of the data that an experienced researcher could quickly check for anomalies. This recommendation would increase the integrity of the data and increase the stature of the dataset as other researchers use the data over time.

Second, posting in-house, high-quality derived data could have great benefits for collaborative research by assuring the use of appropriate and accurate derivation methods. Moreover, when routinely available, derived data become a shared product that may prompt dialogue among researchers. Several discussions were initiated between the Project Office and sites when datasets were complex and the data aggregation or summarization approach was unclear. For example, while implicitly known as being important at the site level, month-long oceanographic cruises carried out three times a year are rarely integrated to give annual estimates. In general, a check on the regularity and frequency of sampling is required before annual estimates are calculated. Researchers used to working with terrestrial data may inadvertently create annual summaries of the data, not being aware of the issues associated with the logistics of cruises and oceanographic sampling. However, if derived data were made available, along with links to the source data from which they were created and the methods with which they were derived, including algorithms and scripts, they would provide a standard in data quality and use and would increase the integrity of the dataset in its entirety.

Recommendations for Project Design

5. Plan for data heterogeneity and "complexities of scale."

Data are collected, quality-checked, and organized in various ways depending on the phenomena sampled (such as bird counts or wind measurements), the spatial distribution (for example, single vs. multiple locations), frequency of sampling (for example, daily vs. quarterly), regularity of sampling (missing days in a daily record, for example), and methods of data collection (for instance, an observer vs. an instrument). Heterogeneity in data management methods adds to the challenge of producing comparable data. For the EcoTrends Project, we focused on time-series data of specific variables which mitigated some effects of incoming data heterogeneity. However, no single programming solution could be developed to automate data handling; programming solutions were developed for single datasets or clusters of similar datasets. To share standardized derived data on a website, data summarization and organization were optimized for display of single variables over specific time aggregations (for example annual bird counts or monthly wind speed). Decisions made to simplify website development, such as only graphing variables through time in the EcoTrends Project, resulted in limitations in the current underlying data structure.

Data are also collected and aggregated at different temporal and spatial units under a variety of circumstances. Scaling from small to large regions and from short to long time periods can involve complex processes. For example, sites collect weather data using a varying number of stations distributed across the land. The EcoTrends Project asked each site to identify "representative" weather datasets from their site. For some sites, particularly those that have relatively flat surfaces, choosing data from site headquarters was sufficient because differences between stations were relatively small. At other sites, however, particularly those with major elevation differences within a small area, choosing a "representative" dataset was difficult. If the EcoTrends Project was expanded to use long-term data from all weather stations at each site, this quandary would be side-stepped only to introduce scaling issues due to an increase in the number of datasets to be handled.

The multiple options for presentation of data also introduce complexities of scale. The initial plan—for a website with static content containing data shown graphically in this book—changed to planning for dynamic data delivery and visualization. The Technical Committee recommended structuring the data and database to support automated metadata generation for derived datasets using existing tools that were under develoment (EML for documenting derived datasets and Metacat for cataloging the resulting EML documents) and tracking data provenance and versioning. This proved to be a significant increase in project scope and requirements for information system design and infrastructure building.

We recommend that, before a multisite synthesis project is completely planned and started, the project leaders recognize and consider carefully the project scope, accounting for the variety and complexity of the source data as well as the constraints associated with their management. Such advance planning is key to adequate and appropriate information management for such synthesis projects. We also recommend that project leaders consider how to best present their data before implementing information management solutions. For example, will the data be presented, as in EcoTrends, as time series? Or will it be expected that different variables will be compared against one another or against non-time-series data? Planning for additional functionality after the project has begun may require changes in how datasets are organized. Therefore, accounting for data heterogeneity and scaling complexity, both in the source data and the resulting data, before the project begins is important. Information specialists trained in both economies of scale and complexities of scale can add insight to project planning (Baker and Chandler 2008).

6. Iteratively design and assess project processes and systems.

Interdependent information environments existed at research sites EPO and LNO. Work at the interfaces of these environments involved an unanticipated amount of coordination and design work as well as mediation, negotiation, and decisionmaking.

The EcoTrends Project started with a linear workflow (traditional for many data management processes), but the workflow rapidly evolved into a cyclical set of processes using feedback from participants to inform further development. Just as the scientific process often does not proceed linearly, there was value in envisioning the data processes as a complex set of interdependent systems, sometimes operating on differing time scales. In the case of the EcoTrends Project, feedback from discussions among various groups subsequently informed further development.

Similarly, data handling cannot be solved by a single technical solution, but rather requires ongoing redesign. ***Our recommendation*** for improving data handling and information management is to plan for modifications, whether in the short term or the long term, according to insights gained and lessons learned throughout the process. For example, when initial assumptions about the readiness and easy access of long-term data and metadata from site web pages proved to be incorrect, the science advisory committee was formed to inform the process of identifying the variables and datasets of interest and the common aggregations to be performed. The project coordinator position was developed to work directly with site personnel to obtain, correct, and understand their data in preparation for inclusion as derived data products and to ensure that committee decisions were followed. As the volume and complexity of the data increased, new communication systems evolved, including ways to share derived data with site contributors. The project coordinator position expanded into an interactive role in both assembling data and creating the derived products needed for the EcoTrends Project and in providing feedback to site personnel on the quality of their data and metadata. Iterative modification of a project may include striving to refine conceptual models of how data are stored and related, continuing design of information systems, working iteratively in phases, and incorporating inquiry-based collaborative learning.

7. Involve advisors from fields who reflect the breadth of the project and who are experienced with information management.

Science-driven ecological synthesis projects may be either narrow, focusing on a single variable over space or over time, or broad with respect to space, time, and/or variables. In either case, advice from experts in the fields that the project embraces is highly useful. The breadth of the EcoTrends Project mandated the collaboration of experts in different fields without which EcoTrends would have fallen short of its goals. When EcoTrends was first started, communications regarding project development were principally between two scientists and site principal investigators because it was thought that the data of interest would be easily accessible online. When it was discovered that the data were difficult or impossible to find, the project was formulated more formally. The science advisory committee was formed to widen the breadth of scientific knowledge and the technology committee was formed to inform technological development (chapter 2). Communications were then expanded to first include researchers from each site, then information managers. The LNO formally became involved when supplemental funding from the National Science Foundation became available.

The combined advice from a wide range of expert contributors had a profound effect on the success of the project. ***We recommend*** for a new synthesis project that the project leader(s) recruit experts whose knowledge spans the breadth of the anticipated project and that they be involved at the start of project planning. This expansion should include not just experts in the focal science but also experts in roles necessary for the implementation of the project, such as information systems designers, information managers, and statisticians.

Recommendations for Improved Information Environments To Support Synthesis Products

8. Focus on development of both local and network information environments.

An "information environment" is a collection of scientists, information managers, and analysts and of the technology needed to manage and share data. Effective information environments involve development of shared language, conventions, and practices for communication among people from different backgrounds. These environments exist at both site and network levels. They include development and use of technical, organizational, and social work processes to manage multiple types of data and the translation of science. Comparing data from multiple sites can stimulate new information management activities and approaches; however, work on collaborative data activities must be constantly balanced with the need to meet site requirements.

The EcoTrends Project needed an effective information environment to successfully manage data and communications. The environment established included a technological system to track, process, and manage data and a communications system to support collaboration and decisionmaking among participating scientists, information managers, and developers. These systems had to develop iteratively with lessons learned from one iteration informing the development of the next. Specifically, these systems promoted understanding of technical and cultural issues regarding data; informed decisions on how data should be selected, processed, and shared; and provided feedback on data handling. Time invested in identifying, developing, and using coordination mechanisms accounted for a large amount of unplanned time that was ultimately recognized as well spent.

We recommend that sites that already have information environments continue to invest in their multifaceted growth and ongoing redesign and that sites without a formal environment dedicate time to developing strategies for creating one, even if resources are scarce. The rewards of a smoothly operating set of practices and systems more than compensate for the cost.

9. Combine long-term data handling with short-term scientific products and data checking procedures.

Throughout the several years that the EcoTrends Project needed to produce its intended products—this book and a complementary website—it was important to keep participants engaged with the project and to share preliminary products. EcoTrends generated both short-term scientific products and periodic data checks requested by the participating sites. The scientific products included papers written by the 2009 scientific working groups. These prompted review of the website content and accessibility, fostered new ideas for future website features and content, and motivated supporters of the project. EcoTrends also developed a data quality report when requesting sites to check their derived data. Created as a spreadsheet and distributed easily by email, this file provided a much needed feedback mechanism for sites and provided a useful, albeit improvised, approach to recordkeeping. Each round of responses from the sites after a data-checking session generated improvements to the report. In the long term, however, a more sophisticated online solution may be more robust, transparent, and user-friendly.

Balancing long-term goals with short-term actions is central to development of a contemporary information environment. Juxtaposing the fulfillment of immediate tasks within a well-defined long-term project creates an environment in which design can be proactive planning for the future while meeting immediate needs. Short-term scientific products, such as papers that examine the data, can justify the usefulness of the project, motivate participants to continue with further development, and inform future development. Data-checking events can validate data processing, elicit feedback from the supporting community, and generate enthusiasm for the project. However, short-term products may require the development of new methods or work-arounds to create them, potentially involving new analysis procedures, communication mechanisms, or types of collaborative activities. These methods or work-arounds can be very useful, but they should inform long-term project development.

10. Develop and maintain transparency by fostering communication and feedback.

Project transparency refers to making participation, processes, and systems accessible and clear for both those closely involved and those casually connected to the project. Transparency requires constant attention to ensure availability of information and openness of the decisionmaking process. While the original intent of the EcoTrends Project was to be open and inclusive, identifying and developing mechanisms for collaboration and documentation took time. Initially, the existing LTER community networking infrastructure—from listservs to use of regular LTER community meetings and monthly information management video conferences—served the project well. However, there was a persistent push to create and continue collaborative activities that would open up discussions concerning data by EcoTrends committees or individual research sites to a public arena that could engage a full spectrum of data providers and users.

The EcoTrends Project Office communication systems evolved in response to projects' and participants' needs. For example, an initial group email request for data submission was followed by individual site communications; committee work with individual hardcopies of graphs evolved to presentation of graphs on an internal website. Presentations at community events improved multisite awareness and engagement. Initial contact with principal investigators and selected members of committees eventually broadened to include information managers and eventually the LTER information management community. The development of a site-specific spreadsheet summarizing dataset submissions created much needed feedback to sites and a coordination mechanism for joint recordkeeping, both within a site and between sites and the Project Office. Graphical representations were referenced online to allow sites to check their contributions.

Attention to project transparency improved both quality and quantity of data submitted, influenced the practice of collaborative science, and promoted buy-in to the EcoTrends Project by participants at all sites.

We recommend that future projects assess the needs of their stakeholders as involved and engaged participants and plan accordingly for project transparency. Research into existing communications systems and online networking tools may help. In addition, we recommend that the project be poised to evolve their communication systems as further needs are perceived.

Conclusions

In this chapter, we presented key lessons learned and recommendations for future synthesis projects from the perspective of a distributed information management team tasked to support network-level ecological research. Alternatively, a site-based research scientist using the data from such a project might have further recommendations on how to best expand analysis teams and develop software routines to statistically explore the data. A software or database developer might have further insights in framing unique, iterative design situations for use in dynamic synthesis environments. Successful planning of any large data synthesis project can be significantly enhanced by the perspectives and knowledge of people from diverse backgrounds and experience.

The EcoTrends Project can be considered a success for the following reasons:

- First, this book, with a diverse array of summarized long-term data collected from 50 sites, and an associated website with some searching and data exploration functionalities fulfill the initial goals of the project.
- Second, EcoTrends contributed significantly to both individual- and community-level understanding of multilevel information management by providing hands-on experience with multisite data integration.
- Third, the EcoTrends Project was unique in carrying out a data production process in a collaborative, interdisciplinary setting with a well-established information management community and in having the information system work distributed between two geographically distinct, but communicating centers (EcoTrends Project Office in Las Cruces, NM, and LTER Network Office in Albuquerque, NM). These arrangements reveal a number of underappreciated dimensions of the work involved in creating comparable data.

In addition to the highlighted successes, the EcoTrends Project demonstrates the importance of addressing and supporting knowledge production, data production, and infrastructure growth within a single framework. The project also highlights the importance of broadening participants' perspectives over time via transparent processes and communication. Specifically, the perspectives of EcoTrends Project participants broadened from simply defining digital products and a single companion workflow to eventually envisioning multiple interdependent data processes and information environments. These processes and environments included not only a technical infrastructure but an array of organizational and social arrangements. Besides just considering the data and the individual work arenas, participants learned to consider the variety of participant roles and activities that tied them together. Iterative, collaborative learning throughout a project and planned flexibility to react to new ideas were important elements of the EcoTrends Project and may well serve any new multisite synthesis project.

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Chapter 17

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

D.P.C. Peters

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).

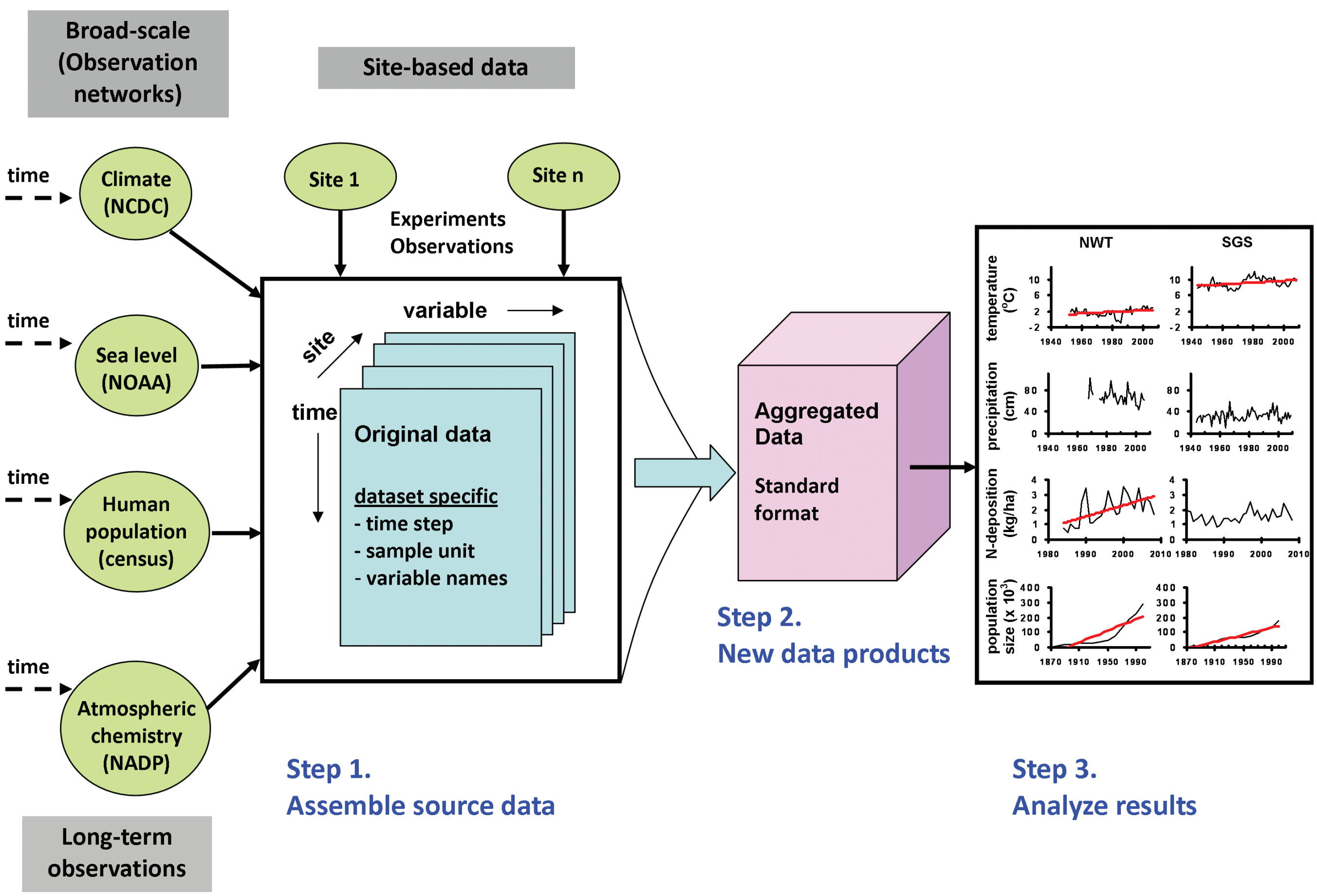

Figure 17-1. Operational framework for assembling different sources of data into a database of new products that allows and encourages cross-site comparisons and synthetic analyses. Redrawn from Peters (2010).

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.

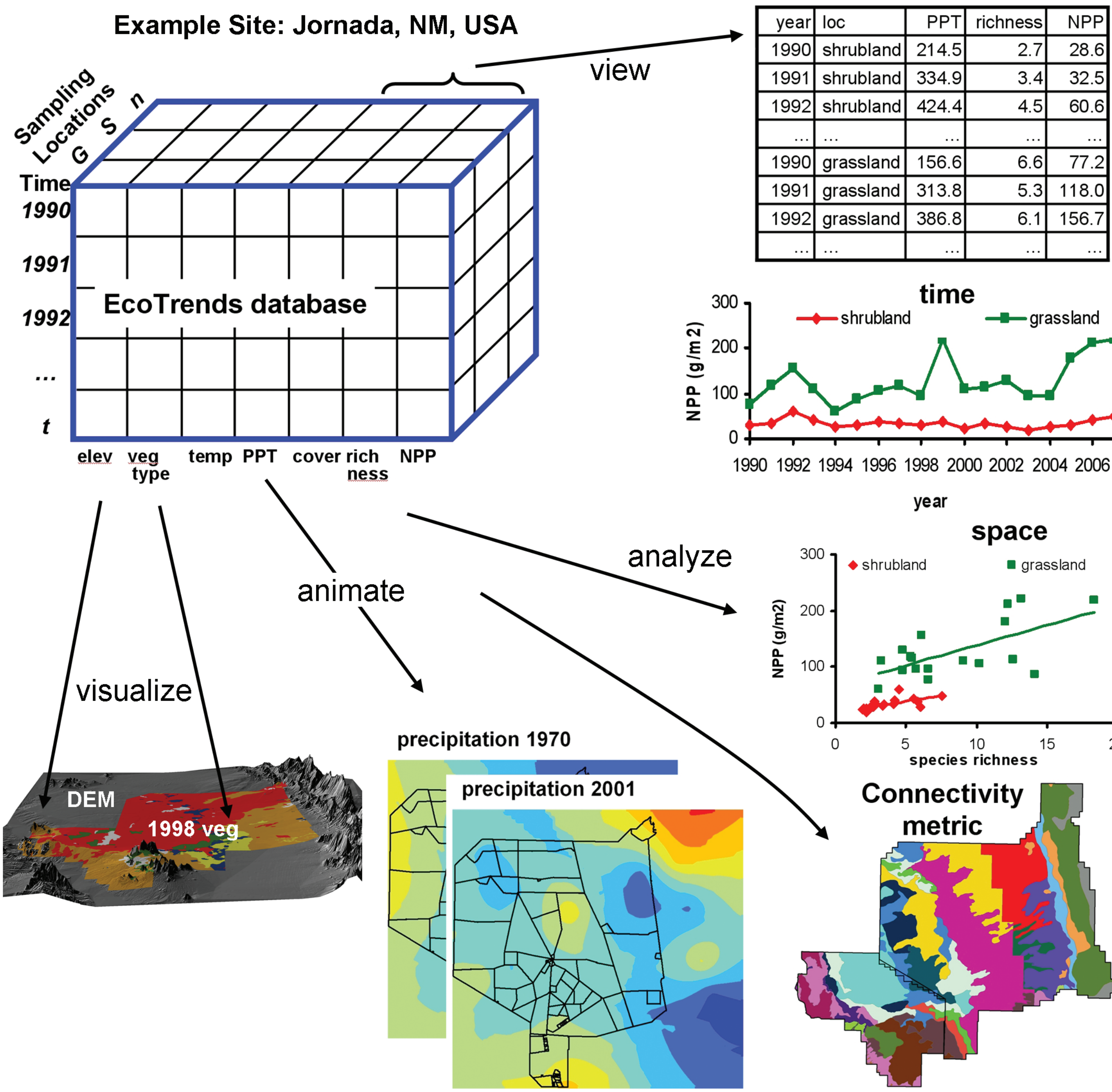

Figure 17-2. Web-based tools that allow visualization, animation, and analysis of derived data products are needed to fully utilize long-term data from many sites to address critical questions from a broad audience.

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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Appendix 1: Site Descriptions

H.J. Andrews Experimental Forest (AND) [USFS, LTER]

http://andrewsforest.oregonstate.edu/

The H.J. Andrews Experimental Forest (AND) was established as an Experimental Forest in 1948 with a focus on research to support forest management and timber production. The emphasis shifted to basic ecosystem research when the site participated in the International Biological Program in the 1970s. In 1980, AND became one of the first LTER sites. The site is located in the western Cascade Range of Oregon in the 15,800-acre (6,400-ha) drainage basin of Lookout Creek, a tributary of Blue River and the McKenzie River. Elevation ranges from 1,350 feet (410 m) to 5,340 feet (1,630 m). Broadly representative of the rugged mountainous landscape of the Pacific Northwest, the Andrews Forest contains excellent examples of the region's conifer forests and associated wildlife and stream ecosystems (figure A1-1).

The climate is cool and wet in winter and warm and dry in summer. Precipitation falls mainly as rain at low elevations and as snow at upper elevations. Soils are primarily Inceptisols, with local areas of Alfisols and Spodosols derived from mainly andesite volcanic bedrock. Surface horizons are commonly loamy but may be stony at depth and shallow on steep slopes. Douglas-fir/western hemlock forest dominates at lower elevations and Pacific silver fir forest at upper elevations. Forest age classes include 150- and 500-year-old stands developed after wildfire and plantations dominated by Douglas-fir that were established after clearcutting since 1950.

Research focus: Since its establishment as an Experimental Forest, the AND has been a site of intensive and extensive research on—

- watershed processes;
- forest ecology, especially structure, composition, and function of old-growth Douglas-fir forests and plantation;
- forest-stream interactions;
- biological diversity;
- processes, rates, and controls on nutrient and carbon cycling; and
- history and effects of natural and management disturbance processes (figure 9-14).

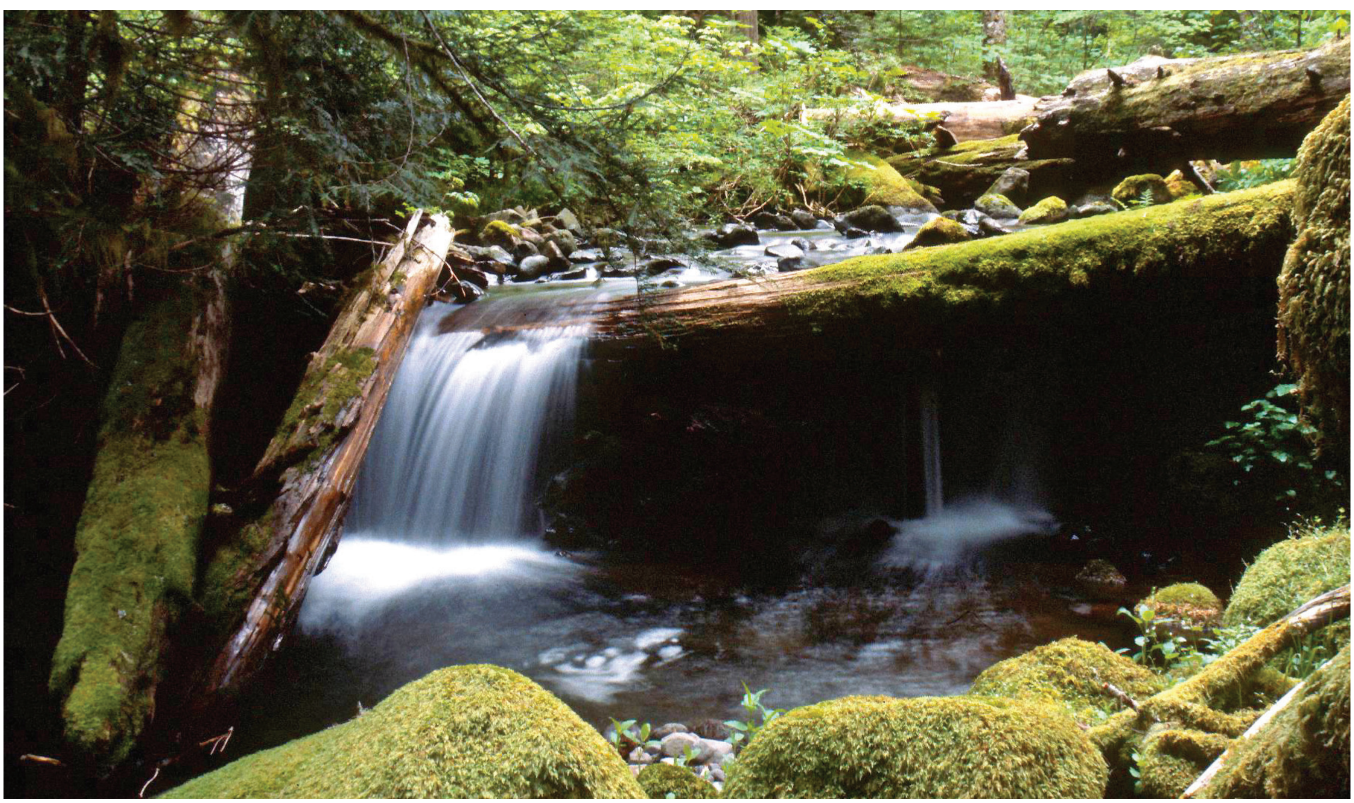

Figure A1-1. The H.J. Andrews Experimental Forest (AND) consists of streams embedded within mountainous coniferous forests. Forest of Douglas fir and western hemlock dominates most of the site, giving way to Pacific silver fir forest at upper elevations. (Photo from AND photo gallery; http://andrewsforest.oregonstate.edu.)

The central question currently guiding AND studies is "How do land use, natural disturbances, and climate variability affect three key ecosystem properties: carbon dynamics, biodiversity, and hydrology?"

Long-term research example: Studies of carbon cycling over the past two decades have revealed that Pacific Northwest forests have exceptional potential for carbon sequestration. The decomposition of logs (downed tree boles) is an important facet of the carbon balance in these forested systems. The first 20 years of a 200-year log decomposition study shows that decomposition depends on the tree species (figure A1-2). During the initial decomposition phase, which was largely the first 4 years, decomposition rates of four common species were similar. As decomposition proceeded, the rates were faster for Pacific silver fir (ABAM) and western hemlock (TSHE) compared with Douglas-fir (PSME) and western red cedar (THPL). The heartwood of the two latter species is decay resistant with THPL being particularly resistant.

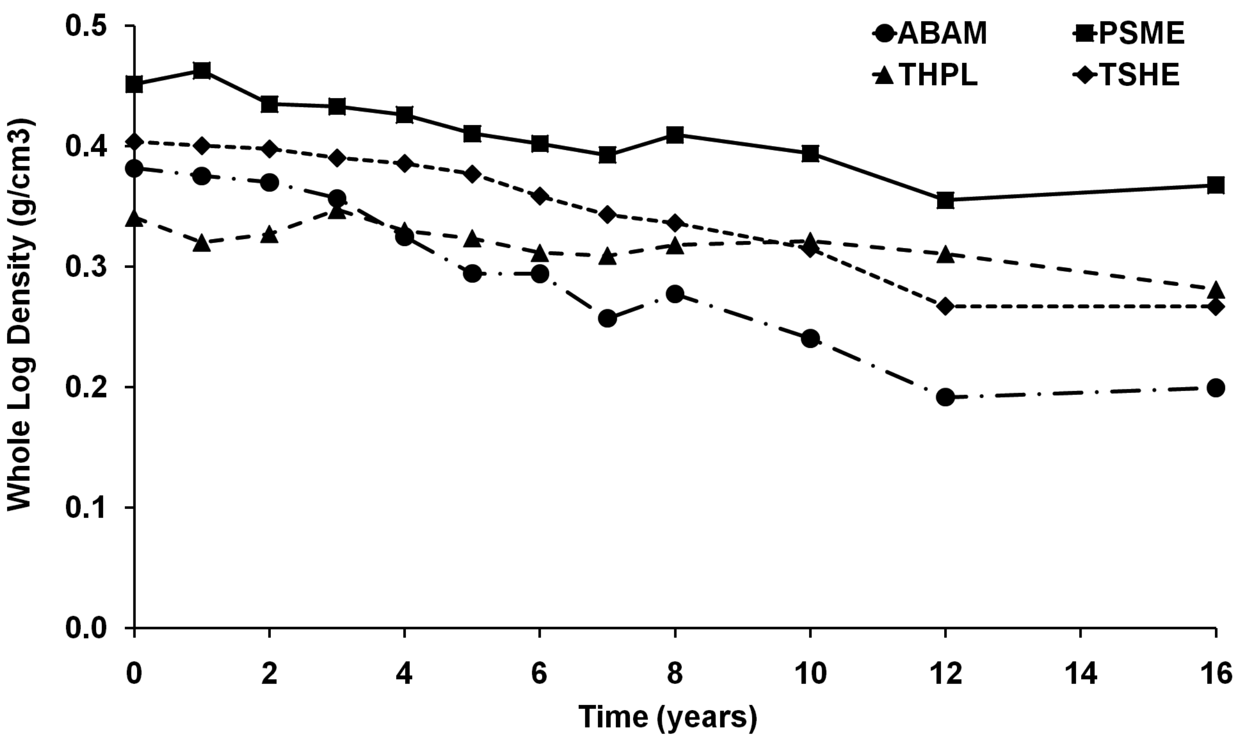

Figure A1-2. Mean density of wood and bark for logs of four species of trees common at the H.J. Andrews Experimental Forest (AND) (details in Harmon 1992). Decomposition rates of the four species were similar for the first 4 years. As decomposition proceeded, rates were faster for Pacific silver fir (ABAM) and western hemlock (TSHE), compared with Douglas fir (PSME) and western red cedar (THPL). The heartwood of the two latter species is decay resistant (Mark Harmon, unpublished data).

Arctic (ARC) [LTER]

http://ecosystems.mbl.edu/ARC/

The Arctic (ARC) LTER site was established in 1987 to understand and predict the effects of environmental change on the ecology of tundra, streams, and lakes. The site is located in the northern foothills of the Brooks Range, Alaska. The region consists of diverse vegetation and animals adapted to the frigid, dry, and windy climate (figure A1-3). Plants are low-growing (no trees) and carry out photosynthesis in a very short growing season. Tussock tundra is the dominant vegetation, but there are extensive areas of wet sedge tundra, drier heath tundra on ridge tops, and river-bottom willow communities. Permafrost (permanently frozen subsoil) is continuous. The streams in the area make up the headwaters of the Kuparuk River, and oligotrophic (low-nutrient) lakes of various ages are abundant.

Research focus: The long-term goal of ARC is to gain an understanding of controls on structure and function of arctic ecosystems through long-term monitoring and surveys of natural variation of ecosystem characteristics, experimental manipulation of ecosystems for years and decades, and synthesis of results and predictive modeling at ecosystem and watershed scales. Effects of global change on arctic systems are of particular importance for the following reasons:

- Global change is predicted to warm the Arctic sooner and more extensively than the rest of the Earth. Several decade-long experiments in heating and nutrient addition are underway in four types of tundra plant communities.
- Arctic soils contain large amounts of organic carbon, enough to double the atmospheric concentration if this carbon were to be oxidized to carbon dioxide when permafrost thaws. Climate warming and human activities in the future will change the water cycle with impacts on permafrost dynamics: too much water will slow down the decomposition of organic matter, whereas too little water will drastically reduce plant growth.

Figure A1-3. The Arctic Long Term Ecological Research (ARC LTER) site is in northern Alaska and has the goal of understanding effects of environmental change on tundra, streams, and lakes. (Photo from ARC photo gallery.)

Long-term research example: Fertilization with nitrogen (10 g/m²/y) and phosphorus (5 g/m²/y) results in a shift in species dominance from a grass-like sedge *(Eriophorum vaginatum)* to a shrub species *(Betula nana)* within 6 years (figure A1-4). *Betula* (dwarf birch) plants also increased in biomass on control plots without fertilization, but not until 11 years later after a decade of warm summers. Woody shrubs are increasing and herbaceous species are being lost throughout the Arctic, likely as a result of warmer temperatures that increase nutrient supply in the soil that favors taller, woody species (Bret-Harte et al. 2001, 2002).

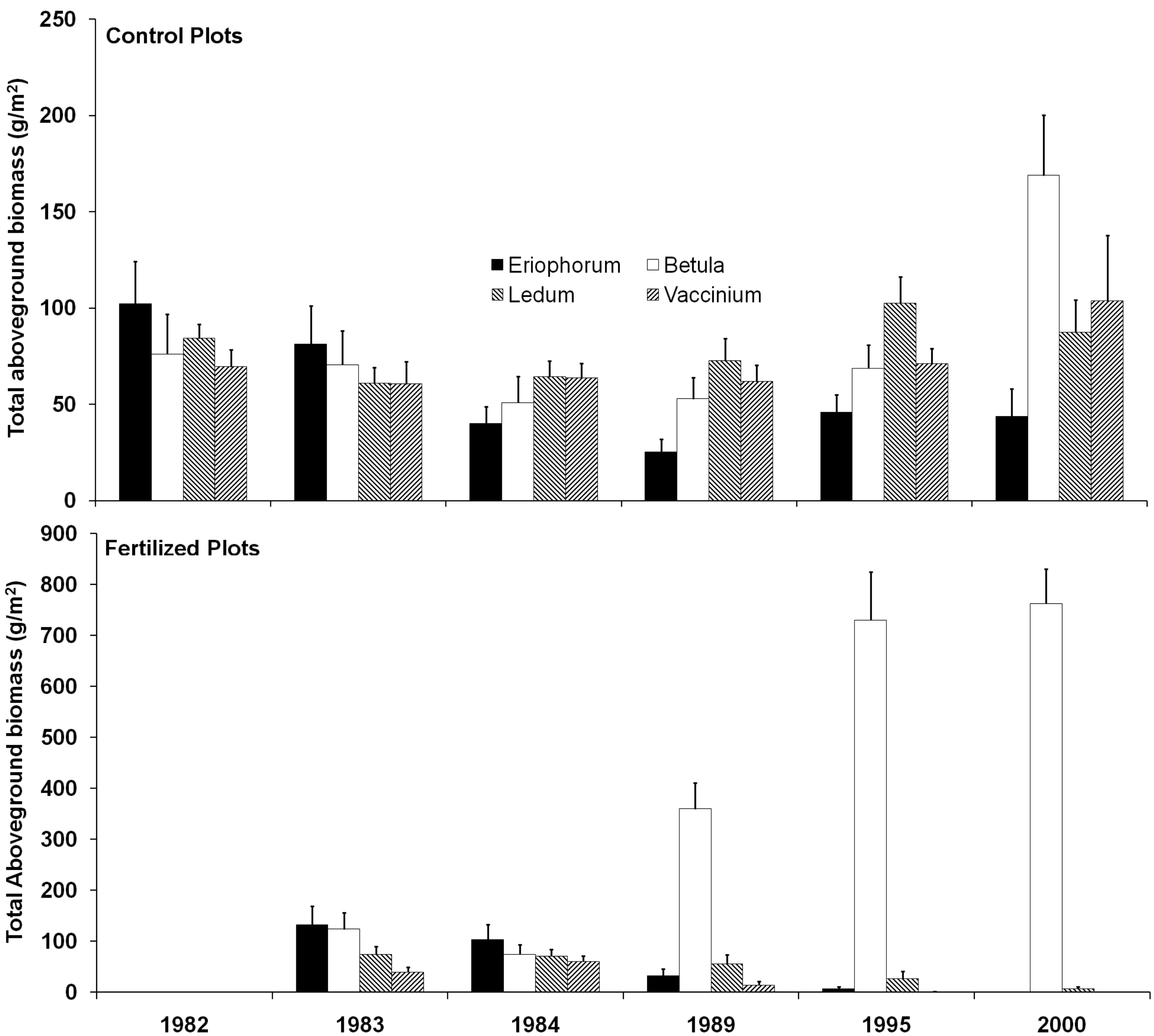

Figure A1-4. Aboveground biomass for four major species in moist acidic tussock experimental plots at the Arctic LTER. Fertilization with nitrogen and phosphorous shifts species dominance from sedges to shrubs within 6 years (updated from Shaver et al. 2001). Data are available at http://ecosystems.mbl.edu/ARC.

Baltimore Ecosystem Study (BES) [USFS, LTER]

http://www.beslter.org/

The Baltimore Ecosystem Study (BES) was established as an LTER site in 1997 to investigate metropolitan Baltimore as an ecological system. The BES conducts research and educational activities in Baltimore City and the surrounding counties (figure A1-5). The project focuses on several watersheds to organize research both spatially and functionally. For example, the Gwynns Falls Watershed encompasses 17,150 hectares and drains into the Chesapeake Bay. The watershed includes agricultural lands, recently suburbanized areas, established suburbs, and dense urban areas having residential, commercial, and open spaces.

Vegetation of the watershed has changed from predominantly forest before European settlement to primarily herbaceous today. There are no original stands of forest in the Baltimore area, although a reference second-growth forested watershed was established in a park in Baltimore County. Research on stream restoration is centered in the Minebank Run catchment. A study of the ecological effects of residential neighborhood greening and restoration is being conducted in a 364-ha storm drain catchment in Baltimore City. A permanent eddy flux tower is located in Baltimore County.

Research focus: The program brings together biological, physical, and social scientists, who collect new data and synthesize existing information to determine how the ecological and built components of Baltimore function and how they are expected to change over long periods. Research aims to provide an integrated understanding of Baltimore as a social-ecological system using several frameworks to support comparative and quantitative urban studies:

- spatial patch dynamics of biophysical and social factors,
- the watershed as an integrative tool, and
- the human ecosystem framework

Figure A1-5. The Baltimore Ecosystem Study Long Term Ecological Research (BES LTER) covers the urban Baltimore, MD, and surrounding areas. (Photo from BES photo gallery.)

These frameworks build on empirical research investigating urban biota, nutrient and energy budgets, and ecological footprints of cities, as well as biotic classifications aimed at urban planning. These frameworks support investigations of—

- the structure and change of the urban ecosystem,
- the fluxes of matter, energy, capital, and population in the metropolis, and
- how ecological information affects the quality of the local and regional environments

These data streams are designed to answer questions about the feedback between social characteristics and actions and ecological patterns and processes. Insights gained from BES research are embodied in regular dialog with Baltimore City, Baltimore County, and State of Maryland decisionmakers and environmental managers. BES approaches and insights have been used in after-school and regular academic curricula in public and private schools in the Baltimore region.

Long-term research example: BES research showed that nitrate concentrations in streams draining agricultural fields are higher than in streams draining urban and suburban areas, with lowest concentrations found in streams draining forests (figure A1-6). Interactions between climate variability and urbanization affect nitrogen losses from streams (Kaushal et al. 2008). These results are important because the mosaic of agricultural, residential, and forested land use is very dynamic in time and space, and there is great concern about nitrogen delivery to the Chesapeake Bay (Shields et al. 2008). The results raise questions in terms of balancing concerns about nitrogen with interest in other ecosystem services provided by agriculture in the landscape.

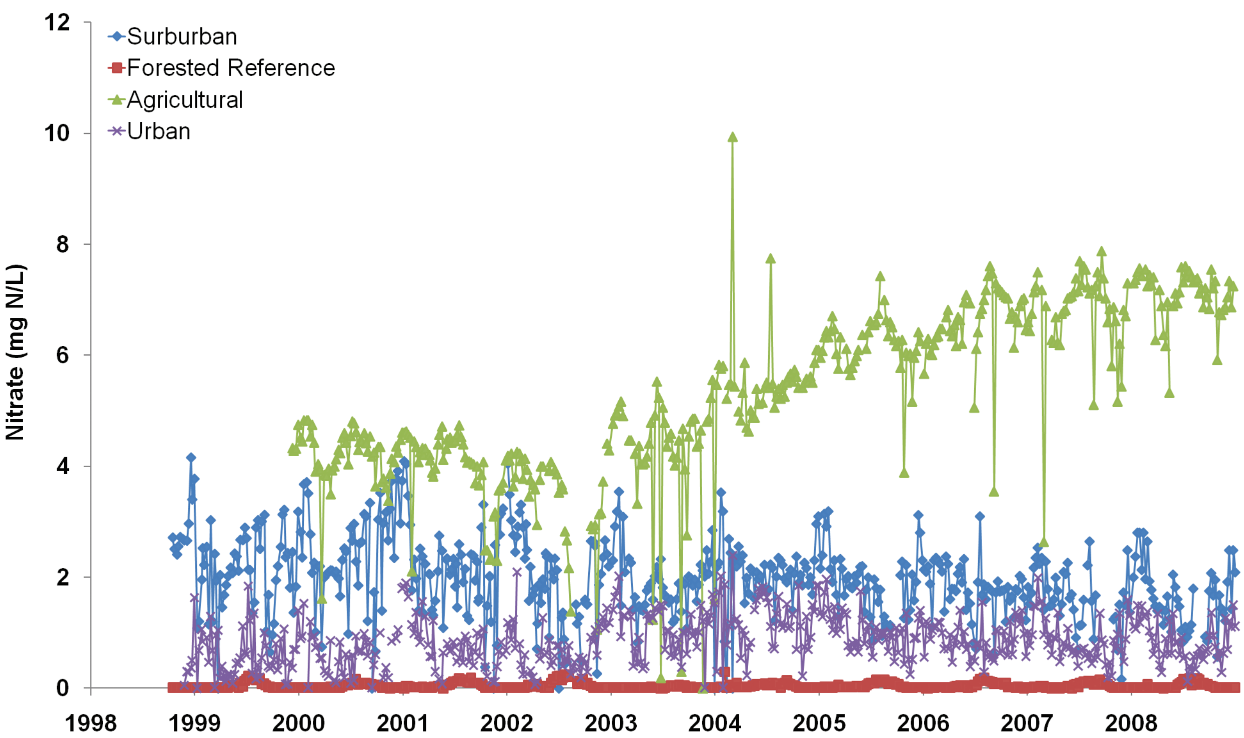

Figure A1-6. At the Baltimore Ecosystem Study (BES), nitrate concentrations in streams from agricultural fields are higher than in urban and suburban areas. Data from 1998-2001 in Groffman et al. (2004). All data are available at http://beslter.org/frame7-page_1.html.

Bent Creek Experimental Forest (BEN) [USFS]

http://www.srs.fs.usda.gov/bentcreek/

The 2,550-ha Bent Creek Experimental Forest (BEN) is the oldest experimental forest in the Eastern U.S., dating to 1916 when the USDA Forest Service acquired much of the Pisgah Forest. Located in the southern Appalachian Mountains, BEN is found on two land type associations: the intermountain valley (Asheville Basin) and the upper-elevation mountain highlands. Asheville Basin soils are Ultisols, and the vegetation is subxeric oak and hickory stands. Dry-site ericaceous shrubs, such as mountain laurel, dominate many forest understories. Mountain highlands soils are Inceptisols that are usually low in fertility. The highlands are forested with oaks and hickories on slopes and ridges. Cove hardwoods, including yellow-poplar and northern red oak, are found on more mesic sites. Rhododendron thickets are common on gently sloping aspects and in drainages. White, shortleaf, Virginia, and pitch pine are common associates.

Research focus. Much of what is known about regeneration and management of southern Appalachian hardwoods stems from research by the Bent Creek staff. Investigations at BEN focus on problems of ecological classification of upland forest ecosystems, forest dynamics, response to silvicultural treatments, and wildlife-habitat relationships. The BEN has an active outreach program that includes a wide array of silvicultural demonstrations and technical training programs.

Blacks Mountain Experimental Forest (BLA) [USFS]

http://www.fs.fed.us/psw/ef/blacks_mountain/

Blacks Mountain Experimental Forest (BLA), in Lassen County, California, was originally designated in 1934 as the Pacific Southwest Station's principal site for management studies of the interior ponderosa pine type. BLA contains about 10,600 acres ranging in elevation from 1,676 m to 2,103 m. Most of the forest is dominated by ponderosa and Jeffrey pine, with white fir and incense-cedar becoming more common at higher elevations. Locally known as "eastside pine," this forest type covers about 2.3 million acres, nearly 14 percent of the total available commercial forest area in California. The forest type also extends south into Baja California and north through eastern Oregon and Washington into central British Columbia.

Research focus. Research at BLA includes an insect-risk rating system to identify large, old ponderosa pines at risk of being killed by the western pine beetle. A 50-year record of stand development has quantified the increase in stand density of white fir and the increased mortality of large, old ponderosa pines found in interior ponderosa pine forests throughout the West in the absence of periodic wildfire (Dolph et al. 1995). In 1933 and 1934, the BLA was completely inventoried on a 1-ha grid. Timber type maps and inventories were updated following harvests. Computerized stem maps for a 20-year period and inventories for a 50-year period are available on 20-acre parcels. A.A. Hasel (1938) conducted research on sampling error in timber surveys at BLA. His seminal work had wide influence on forest inventory methods and is still highly regarded.

Long-term research example. High structural diversity forests (figure A1-7, top) maintain features such as the presence of large, old trees and snags, multiple canopy layers with dense clumps of smaller trees, and many small gaps in the canopy. Low structural diversity forests (figure A1-7, bottom) maintain a single layer of an evenly spaced and continuous canopy and a relatively homogeneous size distribution and spacing of trees.

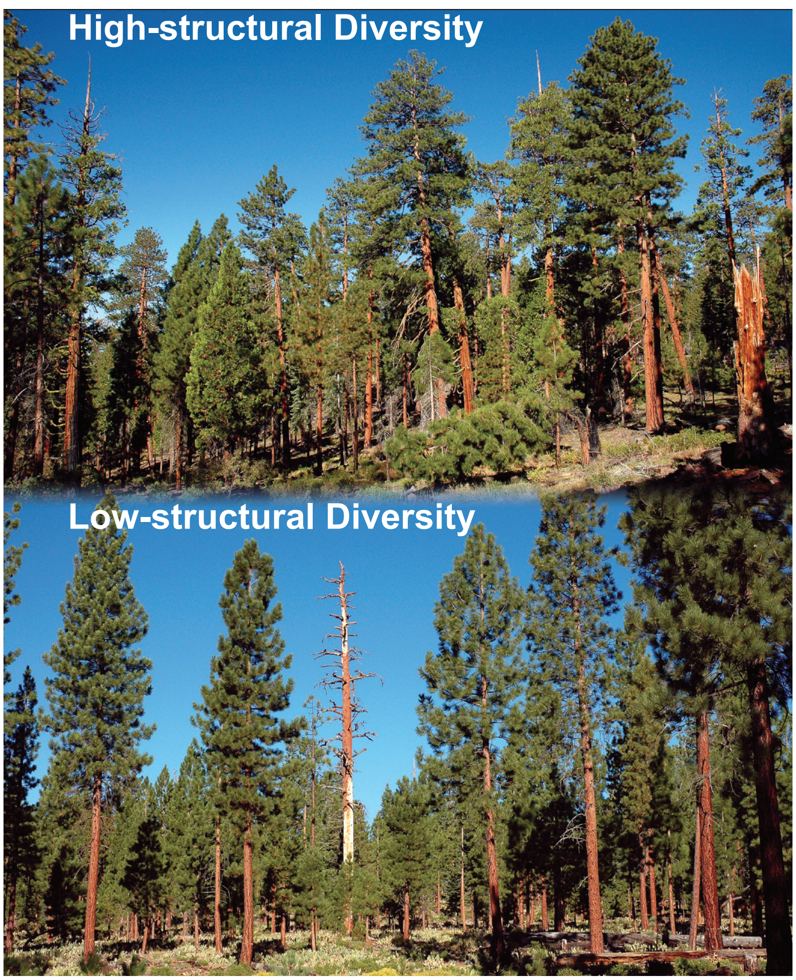

Figure A1-7. The Blacks Mountain Experimental Forest (BLA USFS) has both high- and low-structural diversity forests. (Photo by Todd Hamilton.)

Bonanza Creek Experimental Forest (BNZ) [USFS, LTER]

http://www.lter.uaf.edu/

The Bonanza Creek (BNZ) LTER program was established in 1987 to examine the interactions between climate and disturbance and their effects on ecosystem processes in the boreal forests of interior Alaska. BNZ research is concentrated at two sites near Fairbanks, Alaska. The Bonanza Creek Experimental Forest (BCEF) includes the Tanana River floodplains, upland forests, and wetlands. The Caribou Poker Creeks Research Watershed (CPCRW) is a network of upland forested watersheds (figure A1-8).

Interior Alaska has a continental climate with long cold winters and short warm summers. Permafrost is common in the area, often on north-facing slopes, lowlands, and valley bottoms. Low sun angles create dramatic differences in north-facing and south-facing slopes. The sun stays above the horizon for nearly 22 hours on the summer solstice, but for less than 4 hours on the winter solstice.

Research focus. The BNZ program focuses on improving understanding of the long-term consequences of changing climate and disturbance regimes on the Alaskan boreal forest (figure 9-4). Staff study the dynamics of change in several steps:

- Climate sensitivity of physical and biological processes to temporal variation in the environment, which defines the limits of resilience to climate change
- Changes in the successional dynamics caused by changes in climate and disturbance regime, which define the points in the adaptive cycle of disturbance and recovery at which ecosystems are most vulnerable to change
- Threshold changes that are likely to cause the boreal forest to function in a qualitatively new way
- Integration and synthesis of these modes of climate response across multiple temporal and spatial scales and exploration of their societal consequences

Figure A1-8. The Bonanza Creek Long Term Ecological Research (BNZ USFS/LTER) studies boreal forests of interior Alaska. Here, a fire burns on the Tanana Flats. (Photo by Teresa Hollingsworth.)

The research design combines long-term observations and experiments with short-term process studies to identify ecological changes and to document controls over ecosystem processes and successional dynamics in three landscape units: floodplains, uplands, and wetlands. Plot-level studies are extended to larger spatial scales (watersheds, regions, and the State of Alaska) using modeling and remote sensing.

Long-term research example. Bud burst in an aspen forest on the south-facing slope of Chena Ridge now happens 2 days earlier than in the mid 1970s (figure A1-9). This change in phenology is likely a result of a warming trend in spring temperatures in Alaska during the past several decades and has implications for plant production and the timing of plant-animal interactions in the boreal forest.

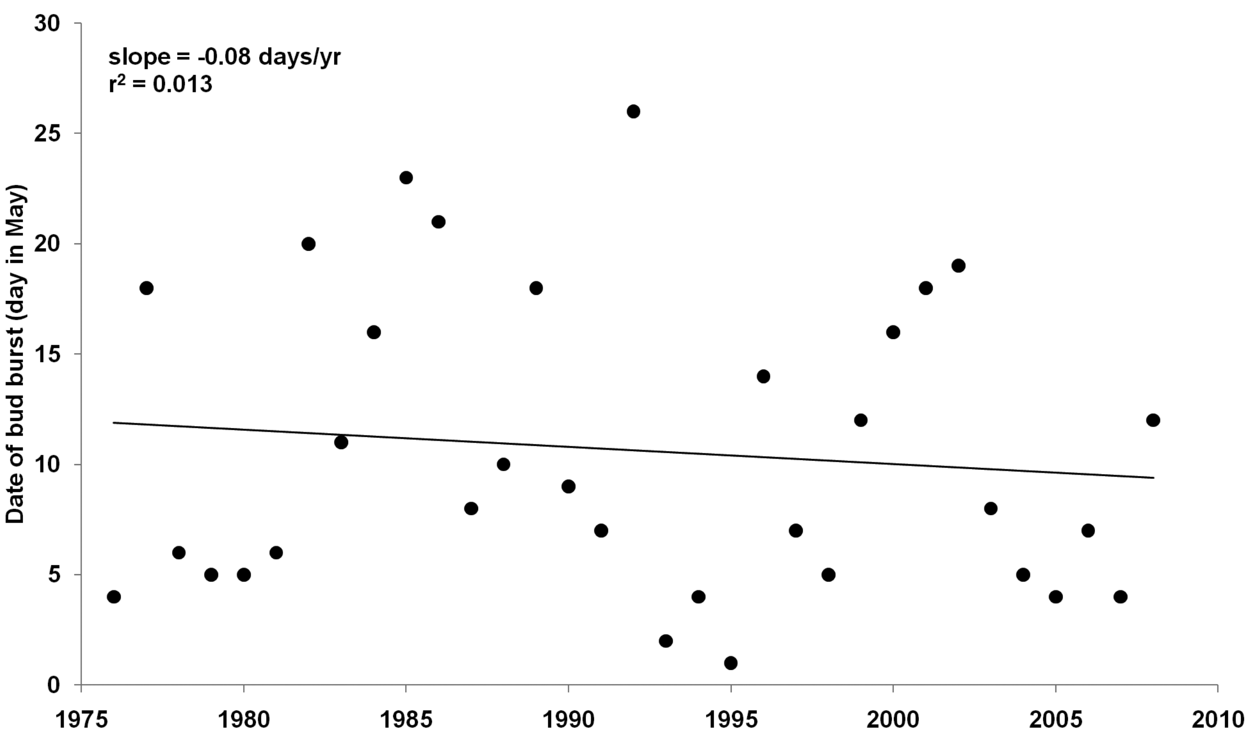

Figure A1-9. Bud burst is now occurring 2 days earlier than in the mid-1970s in an aspen forest at the Bonanza Creek Experimental Forest (BNZ). Data and methods are available at http://www.lter.uaf.edu/data_detail.cfm?datafile_pkey=300.

California Current Ecosystem (CCE) [LTER]

http://cce.lternet.edu/

The pelagic ocean California Current Ecosystem (CCE) site was established as an LTER site in 2004 to understand the processes that govern dynamics of the productive coastal upwelling biomes found along the eastern margins of all major ocean basins. The CCE site encompasses 193,000 km^2 of California coastal waters extending from San Diego northward beyond the major upwelling site at Point Conception and from the shoreline to approximately 500 km offshore (figure A1-10).

The ocean circulation system in which the CCE site is embedded, called the California Current System, is part of the clockwise circulation pattern of the North Pacific Ocean. This system modifies weather patterns and the hydrologic cycle of much of the Western United States and plays a vital role in the economy of numerous coastal communities. The ecosystem sustains active fisheries of a variety of finfish and shellfish and provides essential habitat for many invertebrates, marine mammals, seabirds, and kelp forests.

Research focus. Sixty years of climate and ecosystem observations by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program have characterized ecosystem variability on multiple time and space scales and help form the foundation for

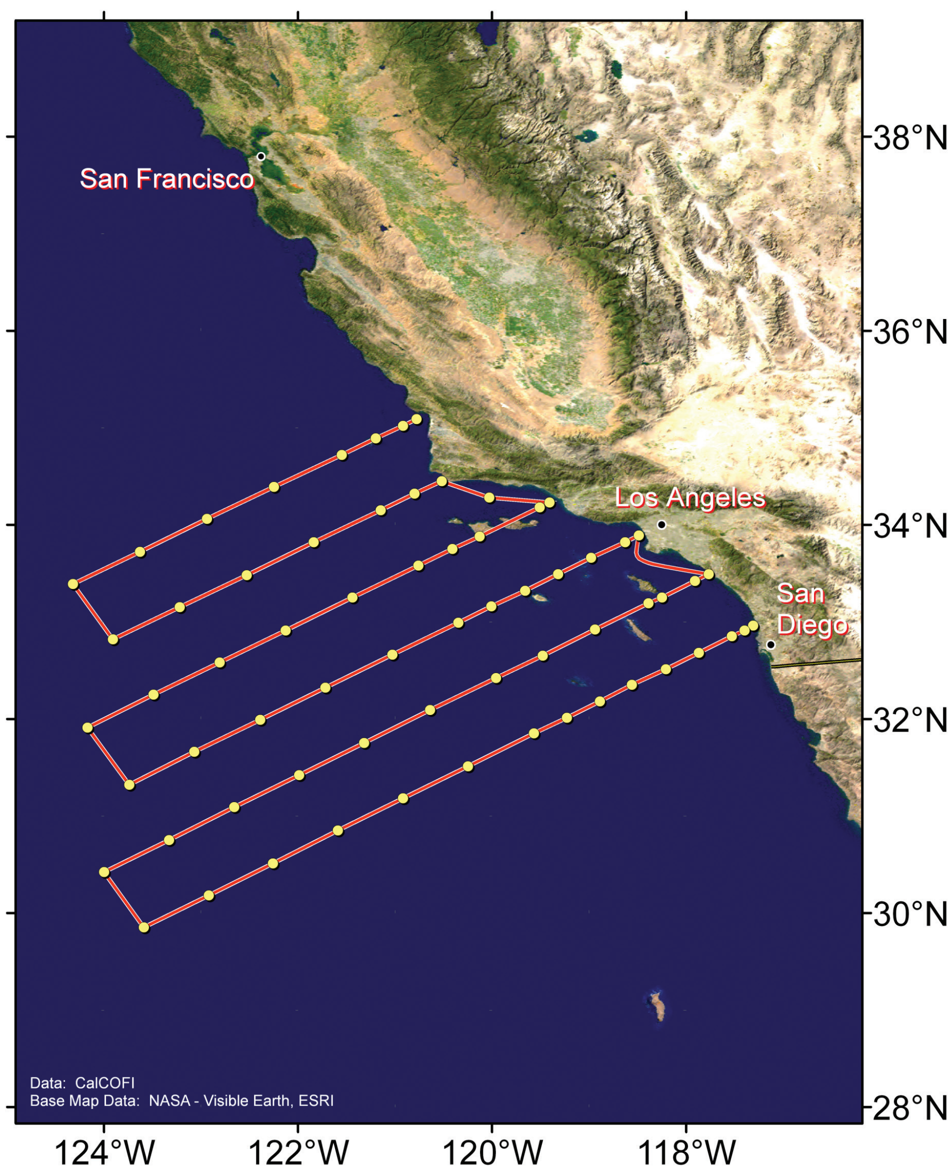

Figure A1-10. The California Current Ecosystem Long Term Ecological Research (CCE LTER) studies pelagic systems off the coast of California. The sampling grid builds on the transect lines of CalCOFI, currently consisting of six tracks extending from nearshore to offshore, along which shipboard observations are made quarterly at 66 stations. Image by Thomas J. Moore. (Base map imagery source: NASA Visible Earth/ESRI.)

CCE research. The CCE site seeks to understand how multiple scales of climate forcing lead to altered structure and dynamics of the pelagic ecosystem and how ocean productivity and biodiversity may change in the future.

The water column food web is markedly affected by physical ocean characteristics such as variations in upwelling, turbulent mixing, density stratification, and ocean circulation. This linkage to the physical environment is particularly apparent for planktonic organisms near the base of the food web (figures 3-2, 3-6). The CCE study site encompasses diverse planktonic communities in different physical environments, ranging from upwelling-dominated assemblages to stably stratified offshore assemblages typical of the subtropical gyres. The CCE group uses the spatial variability in plankton assemblages in different parts of the study site as an analog of how a single region may change over time.

Long-term research example. The ocean environment has changed in the California Current ecosystem over the past 5 1/2 decades, including a relatively abrupt ecosystem shift in the mid 1970s that resulted in an increase in average water column stratification in the CCE region (figure A1-11a), as well as a warming over the broader Northeast Pacific reflected in the Pacific Decadal Oscillation Index (figure A1-11b). Zooplankton showed a marked increase in biomass of the euphausiid (krill) *Nyctiphanes simplex* and a tendency for more outbreaks of the rare doliolid *Doliolum denticulatum* (figure A1-11c, d). Conversely, a group of salp species that predominated in the cool phase of the California Current disappeared locally (figure A1-11e). Whether or not reciprocal ecosystem changes occurred following the La Niña cooling of 1999 remains in question.

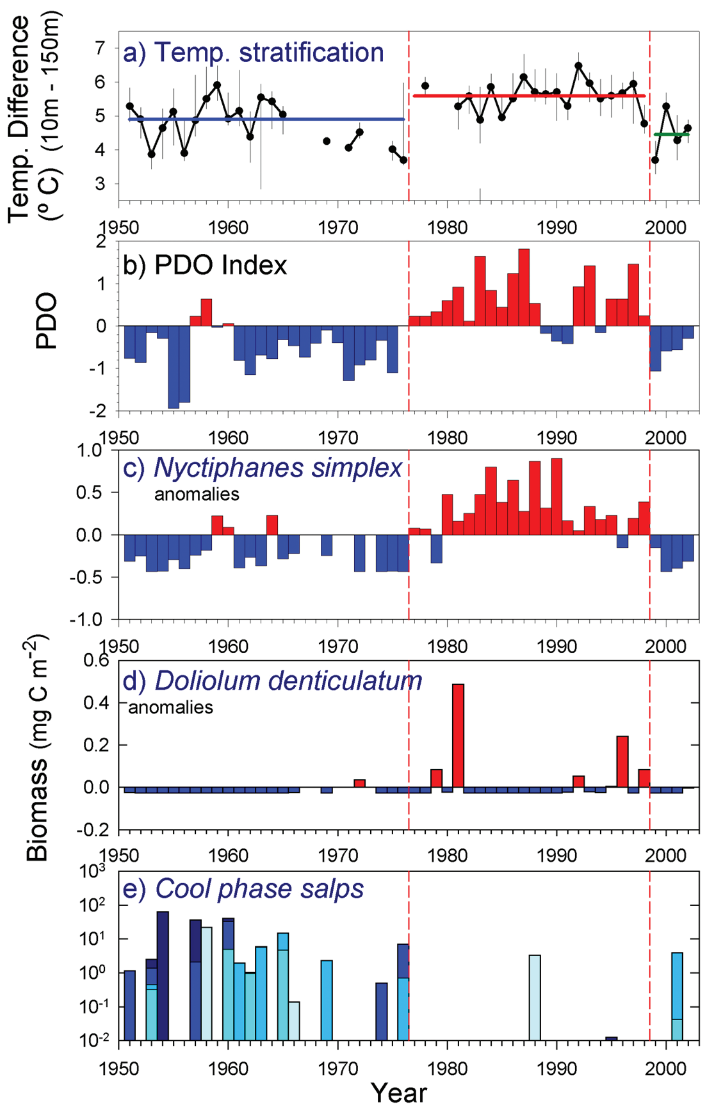

Figure A1-11. Altered (a) ocean temperature stratification and (b) the Pacific Decadal Oscillation (PDO) are resulting in (c-e) low-frequency changes in the California Current Ecosystem (CCE) zooplankton assemblage (Ohman and Venrick 2003). Reprinted with permission from The Oceanography Society.

Cascade Head Experimental Forest (CHE) [USFS]

http://www.fsl.orst.edu/chef/

The 11,890-acre Cascade Head Experimental Forest (CHE) was established in 1934 for scientific study of coastal Sitka spruce/western hemlock forests found along the Oregon Coast. In 1974, Congress established the 9,670-acre Cascade Head Scenic Research Area (SRA) that included the western half of the experimental forest, several prairie headlands, the Salmon River estuary to the south, and contiguous private lands. In 1980, the entire area was designated a Biosphere Reserve as part of the United Nations Biosphere Reserve system.

Sitka spruce and western hemlock dominate the forest from the coastal edge to 3 to 4 km inland. At this point, Sitka spruce begins to drop out and Douglas-fir density increases. Western hemlock is found throughout the forest. Some of the highest growth rates and greatest volumes per hectare for any temperate forest in the world are reported for this area. Soils, derived primarily from tuffaceous siltstones, are fine textured, moderately well drained, and very deep (more than 1 m). Soils under forest stands are fertile, rich in organic matter, and contain high levels of nitrogen.

Proximity to the Pacific Ocean results in a moderate and very wet climate. Heavy rains and gale-force winds blowing off the ocean are common in late fall and winter. Extensive blowdown and wind-pruning of trees are evidence of these severe storms (figure A1-12).

Research focus. The primary research goals of CHE and SRA are—

- to encourage scientific study while promoting a sensitive relationship between humans and their environment,
- to promote scientific understanding of how forest and wetland ecosystems relate to human use, disturbance and coastal biodiversity, and
- to provide educational and research opportunities to students and scientists from a variety of agencies and institutions.

Figure A1-12. The Cascade Head Experimental Forest (CHE USFS) occurs in the coastal Sitka spruce-western hemlock forests along the Oregon coast. Research evaluates effects of natural disturbances, such as windstorms, that occur regularly at the site. (Photo by Sarah Greene.)

Caspar Creek Experimental Watershed (CSP) [USFS]

http://www.fs.fed.us/psw/ef/caspar_creek/

Caspar Creek (CSP) is the site of long-term research on the effects of timber harvest on streamflow, water quality, sedimentation, and aquatic life in the rainfall-dominated, forested watersheds of the northern coast of California. CSP was established in 1961 as a cooperative effort between the California Department of Forestry (CDF) and the USDA Forest Service's Pacific Southwest Research station (PSW). Study basins include the North Fork (473 ha) and the South Fork (424 ha), each with nested sub-basins.

Conditions are typical of the redwood-dominated areas of California (figure A1-13). Winters are mild and wet, while summers are moderately cool and dry. About 95 percent of the average annual precipitation of 1,200 mm falls from October through April. Summer coastal fog is common. Snow is rare, and rainfall intensities are low. The principal soils are well-drained loams to very gravelly sandy clay loams, 1 to 2 m in depth, and derived from weathered graywacke sandstone and shale of the Coastal Belt of the Franciscan Assemblage of early Cenozoic age. Soils have high hydraulic conductivities. Subsurface stormflow is rapid, producing saturated areas of only limited extent and duration.

The second-growth mixed conifer forest includes coast redwood *(Sequoia sempervirens),* Douglas-fir *(Pseudotsuga menziesii),* western hemlock *(Tsuga heterophylla),* grand fir *(Abies grandis),* and tanoak *(Lithocarpus densiflorus).*

Research focus. Basin-scale treatment-control experiments in CSP have been used to study the effects of forest practices on watershed processes (Ziemer 1998). In the first experiment, the North Fork served as the control while two-thirds of the stand volume of the South Fork was selectively harvested and tractor-yarded from 1971 to 1973. Erosion was monitored on hillslope plots, while runoff, suspended sediment, and accumulated bed material were measured at the outlet weirs (Rice et al. 1979). From 1989 to 1991, about 37

Figure A1-13. North Fork Caspar Creek (foreground), 15-17 years after portions of the watershed were clear-cut logged. Part of the Caspar Creek Experimental Watershed (CSP USFS), the area is dominated by second-growth mixed conifer forest. (Photo from USFS archives.)

percent of the North Fork watershed was harvested (Lewis et al. 2001). This study pioneered methods for automatically collecting suspended sediment samples based on real-time flow measurements and allowed development of methods for continuous estimation of suspended sediment loads using turbidity records (Lewis and Eads 2001). These records may be the most temporally and spatially detailed of suspended sediment collected.

Long-term research example. Departures from pretreatment regressions relating storm event loads from two clearcut tributaries (CAR and EAG) to event loads in untreated control watersheds illustrate trends in sediment production after logging (figure A1-14). After initial harvesting, watershed EAG was burned (year 1) and herbicided (year 3) to control brush regrowth, and both watersheds were thinned at year 11. During the pretreatment period, departures are regression residuals and average to zero as expected. After harvesting, an abrupt increase in loads is accompanied by an increase in variance, and a second period of increased loads is associated with thinning of regrowth. While the magnitude of response differs between the two watersheds, the temporal pattern of variation is similar, reflecting the same sequence of treatments and storms.

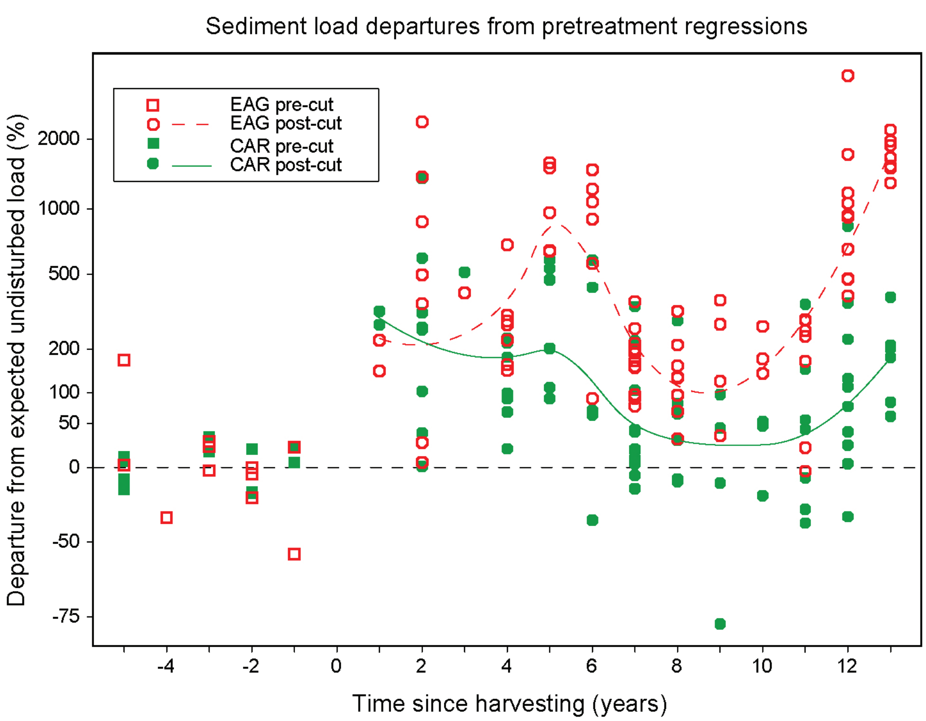

Figure A1-14. Sediment loads as a departure from pretreatment values at Caspar Creek Experimental Watershed (CSP). After harvesting, load values and variability increase for two watersheds (Jack Lewis, unpublished data).

Cedar Creek Ecosystem Science Reserve (CDR) [LTER]

http://www.cbs.umn.edu/cedarcreek

Cedar Creek Ecosystem Science Reserve (CDR) was established in 1940 and was funded as an LTER site starting in 1982 to improve understanding of the processes that govern the dynamics and functioning of ecosystems located along the boundary between prairie and forests. This region has a continental climate with cold winters and hot summers. Much of the site is covered in wetlands, including white cedar *(Thuja occidentalis)* and ash swamps, acid bogs, wet meadows, and marshes. Upland areas consist of variety of habitat types, including—

- savanna areas with a sparse canopy of burr oak *(Quercus macrocarpa),*
- prairie openings largely dominated by little bluestem *(Schizachyrium scoparium),*
- dry oak woods dominated by pin oaks *(Quercus ellipsoidalis),*
- smaller stands of hardwood forests with a large component of basswood *(Tilia americana)* and sugar maple *(Acer sacharrum),* and
- white pine *(Pinus strobus).*

Research focus. CDR research examines the population, community, and ecosystem impacts of human-driven environmental changes (figure 3-7). Research focuses on the causes and consequences of biodiversity. Following a severe drought in 1989, plant diversity had a stabilizing effect on productivity (Tilman 1996). Experiments were then established to test hypotheses about diversity effects and the underlying mechanisms (figure A1-15). A related experiment (BioCON) was established to study interactions between species diversity and elevated levels of atmospheric CO_2 and nitrogen deposition.

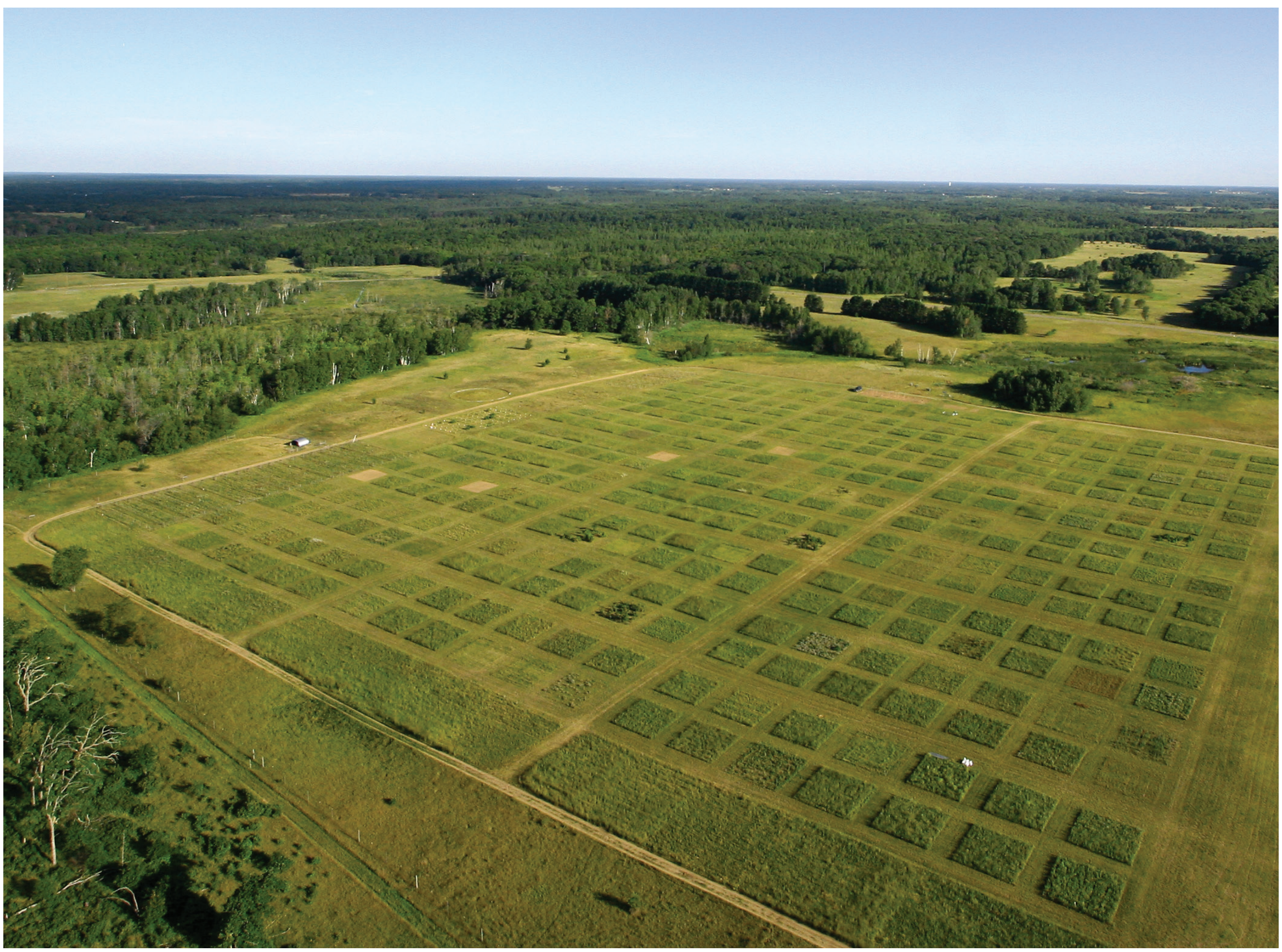

Figure A1-15. Experiments at the Cedar Creek Long Term Ecological Research (CDR LTER) in central Minnesota are designed to study the causes and consequences of biodiversity. (Photo by David Tilman.)

Long-term research example. Changes in ecosystem properties as affected by both broad-scale climate effects (drought) and landscape-scale effects on species are illustrated by data from CDR. Aboveground biomass decreased during the 1987-1988 drought, yet is generally increasing through time and more than doubled between 1991 and 2004 (figure A1-16, top). This increase is mainly due to an increase in legumes (e.g., *Lathyrus venosus*; veiny pea) caused by decreased deer herbivory. Plant species richness also decreased during the drought with recovery by 1993 (figure A1-16, bottom). The loss of species following 1991 was in response to fragmentation caused by nitrogen addition to adjacent plots. These results are important to our understanding of system response as temperatures increase with global warming, and landscape fragmentation occurs with landuse change.

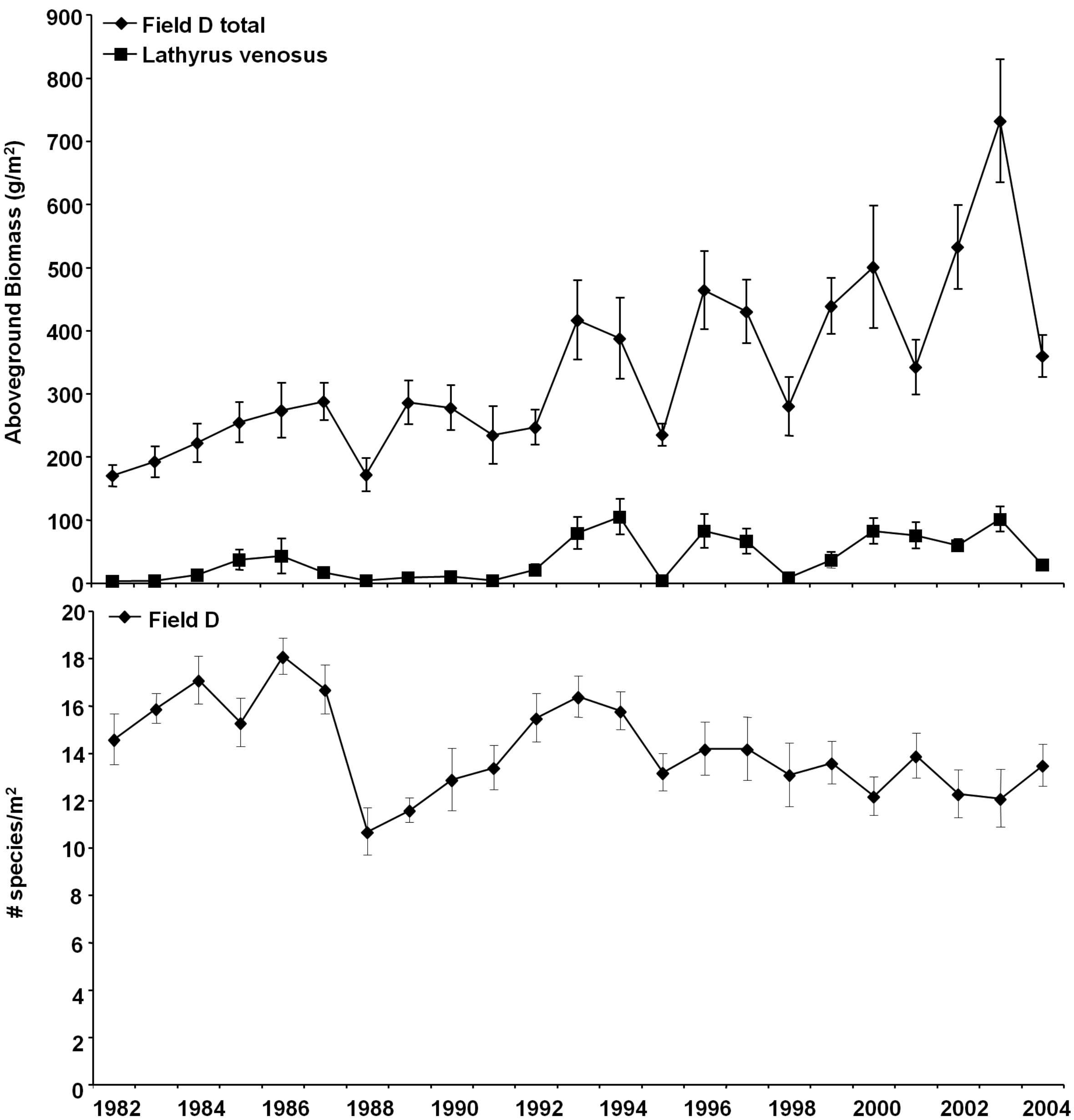

Figure A1-16. Drought responses at the Cedar Creek Ecosystem Science Reserve (CDR): top, aboveground biomass increases through time as a result of decreasing deer herbivory and an increase in legumes (*L. venosus*). Bottom, species richness decreases with landscape fragmentation (David Tilman, unpublished data).

Central Arizona-Phoenix (CAP) [LTER]

http://caplter.asu.edu/

The Central Arizona-Phoenix (CAP) site was established as part of the LTER Network in 1997 to study human interactions with the environment in central Arizona and the Phoenix metropolitan area. The study area is in a 6,400 km^2 area where two major desert tributaries of the Colorado River (the Salt and the Gila) converge. The basin once supported a vast expanse of lowland Sonoran desert and riparian systems and now houses the Nation's fifth-largest city (figure A1-17). The study area contains some of the fastest-growing municipalities in the United States, enabling researchers to study the effects of rapid urbanization on an arid ecosystem.

As agriculture and, increasingly, desert lands give way to homes and businesses, natural habitats are severely modified with significant ramifications for native plant and animal species. Water quality and quantity issues are pressing, and air quality remains a critical problem due to ozone pollution and high levels of particulate matter. Other stressors include drought and the urban heat island effect, which has raised nighttime minimum temperatures by 5 °C.

Figure A1-17. Central Arizona-Phoenix Long Term Ecological Research (CAP LTER) studies urban ecosystems and their effects on the surrounding desert. (Photo from CAP photo gallery.)

Research focus. CAP researchers are examining the function and structure of the urban ecosystem, the feedbacks between human decisions and ecological processes, and the effects of urbanization on surrounding desert land. Land-use change is viewed as a major driver of ecological patterns and processes at multiple scales (figure 9-19). Research also seeks to understand the responses, both human and ecological, that accompany changes in ecological conditions and multiple feedbacks in the system that lead to further change.

CAP has four main objectives:

- To advance ecological understanding through development of ecological theory
- To understand the structure and function of the urban ecosystem
- To develop ecological scenarios that can be used to guide future development of urban environments while sustaining ecological and societal values and to engage decision makers in this process through deliberate knowledge exchange
- To involve the public in the research effort through dissemination of information via the media, public outreach, and educational initiatives

Long-term research example. The Phoenix metropolis arose from its agricultural beginnings over the course of around 100 years. Documenting this change in coarse land-use categories involved compilation of data from air photos, satellite images, and on-the-ground land categorization. Settlement began in the late 1800s, and by 1912 irrigated agriculture surrounded small, isolated towns (figure A1-18). Whereas early land conversion was from desert to agriculture and agriculture to urban, in more recent years direct desert to urban conversion has become prevalent. Expansion of agricultural lands continued until 1975. The most dramatic land change began in the 1950s, when urban areas increased in size and began to coalesce. By 2000, much of central Arizona was urban with infilling of housing and buildings that continues today. These changes, and the legacies of former land use, are important determinants of present-day ecological pattern and process. Trends of land change seen in central Arizona through time and space are typical of smaller cities in the Southwestern United States.

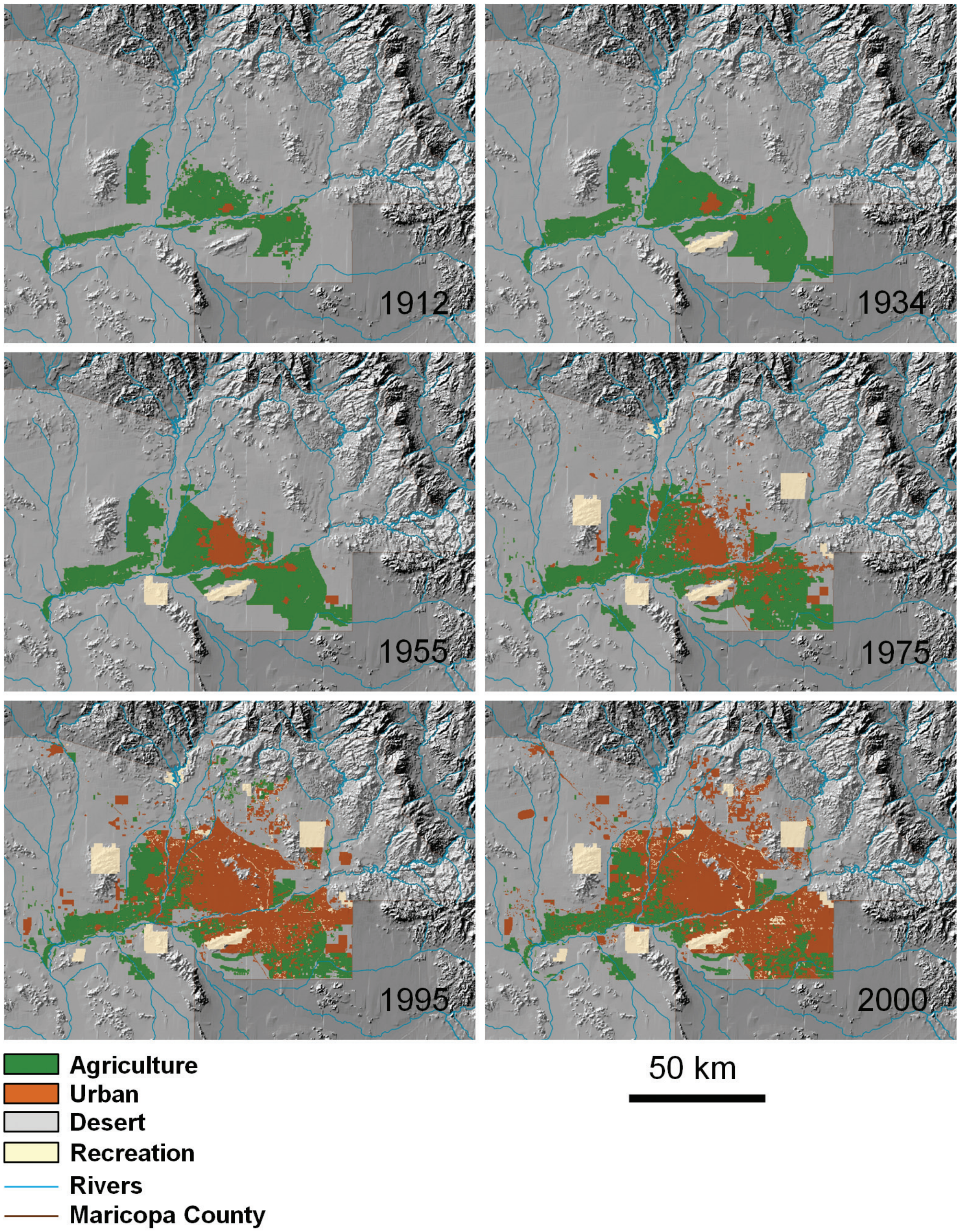

Figure A1-18. The Phoenix area shifted from predominantly desert to agricultural land in the early 1900s. A major shift from agricultural land to urbanization occurred after 1950. More recently, desert is being converted to urban areas (Knowles-Yanez et al. 1999). Reprinted with permission from Central Arizona-Phoenix LTER.

Coweeta (CWT) [USFS, LTER]

http://coweeta.ecology.uga.edu/

The Coweeta Hydrologic Laboratory (CWT), a USDA Forest Service Research Station, was established in 1934 as a testing ground for certain theories in forest hydrology; it was established as an LTER site in 1980. The site is located in the Nantahala Mountain Range of western North Carolina, and consists of two adjacent east-facing, bowl-shaped basins. Coweeta Basin (1,626 ha) is the primary site for watershed experimentation, and Dryman Fork Basin (559 ha) is held in reserve for future studies.

The climate is humid subtropical at the lowest elevations and marine humid temperate at the higher elevations. Winters and summers are mild; there is little snowfall, and summer days with temperatures exceeding 30 ºC are rare. Rainfall is evenly distributed throughout the year, with considerable spatial variability related to elevation and latitude. Precipitation generally increases about 5 percent per 100 m of elevation gain along an east-west axis. The dominant vegetation is temperate deciduous forest (figure A1-19), although the intermixing of "northern" and "southern" taxa results in one of the most biodiverse regions of North America.

Figure A1-19. Temperate deciduous forest is the dominant vegetation at the Coweeta Long Term Ecological Research (CWT USFS/LTER) site in western North Carolina. (Photo from CWT photo gallery.)

Research focus. CWT research has contributed to the growing understanding of how human practices can influence forest and stream ecosystems at numerous scales. For example, bottom-up effects of nutrient enrichment in a detritus-based ecosystem can stimulate whole-community production and cause large changes in carbon balance and consumer productivity. These changes have important implications for the contemporary die-off of eastern hemlock *(Tsuga canadensis)* from the infestation by the hemlock woolly adelgid *(Adelges tsugae)*. The CWT LTER project has achieved an understanding of complex interactions between environmental gradients, disturbance, and land use that underpin the transformation of the Old South into the "New South" in ways that can accommodate the growing demand on research to provide solutions for environment and society.

Long-term research example. Research from CWT shows the importance of monitoring large numbers of individual trees and of measuring trees over long periods. Individual trees have been measured over time to estimate growth (figure A1-20). Both red maple and white pine trees show wide variation in growth of the basal area of the trunk through time. Some trees grow very little from one year to the next, whereas other trees of the same species located nearby show high growth rates. Thus, growth rates may be related to fine-scale variation in environmental conditions (such as soil properties) and within-species genetic variability rather than broad-scale climatic conditions.

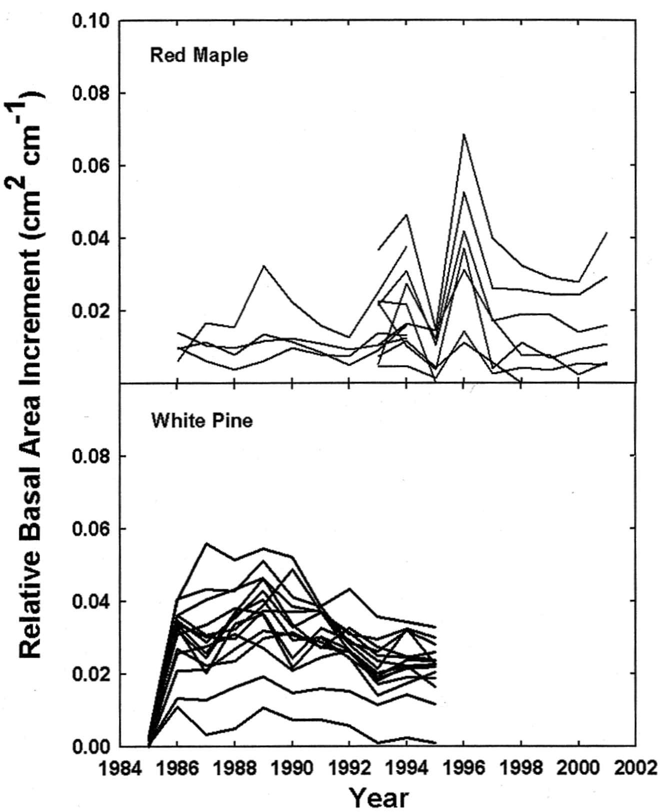

Figure A1-20. The relative basal area increment (cm^2 tree growth per cm tree diameter) of two selected species at Coweeta (CWT). Each connected line represents a single tree over the measurement period. The deciduous red maple *(Acer rubrum)* and the evergreen white pine *(Pinus strobus)* exhibit wide variation of relative basal area increment between trees (Kloeppel et al. 2003). Reprinted with permission from Oxford University Press.

Crossett Experimental Forest (CRO) [USFS]

http://www.srs.fs.usda.gov

In 1934, the Crossett Experimental Forest (CRO) was established as the first USDA Forest Service branch research station in the South. The CRO supports research on forest management in second-growth loblolly and shortleaf pine stands for forest managers and landowners. The research mission is to develop and evaluate low-cost silvicultural techniques and management alternatives suitable for natural stands on private, non-industrial timberlands in the Mid South. Research is conducted in the following major areas:

- Establishment, development, and growth of forest reproduction
- Stand dynamics, including growth, yield, regulation, and site quality
- Rehabilitation of understocked loblolly and shortleaf pine stands

Long-term data sets. Long-term data sets are available that include stand dynamics and development, annual seedfall data, trends in stand structure and timber volume in a comparative study of different silvicultural practices in southern pines, and trends in stand structure and timber volume in a long-term demonstration of the uneven-aged selection method in southern pines.

Eastern Oregon Agricultural Research Center (EOA) [USDA-ARS]

http://oregonstate.edu/dept/EOARC/

The mission of the Eastern Oregon Agricultural Research Center (EOA) is to provide the scientific basis for sound land and livestock management in eastern Oregon. The beginnings of EOA date to 1911, when the Harney Branch Station was established. After about 20 years, it became clear that the area was not suited to row crops, and the focus shifted to forage and livestock production. During the late 1930s, the U.S. Department of the Interior established the 6,475-ha Squaw Butte Range Livestock Station west of Burns, OR. In 1944, the Harney and Squaw Butte stations were merged, and 260 hectares of flood meadow was purchased by Oregon State University.

The climate is characterized by a short growing season with an average of 65 days between killing frosts. Soils range from sandy loams to heavy clays with a mosaic of areas with high salinity and alkalinity. Major plant communities are sagebrush steppe (basin big sagebrush, Wyoming big sagebrush, mountain big sagebrush, low sagebrush, and black sagebrush) and western juniper woodlands (figure A1-21). These communities are characterized by woody species in the canopy and by grasses, such as bluebunch wheatgrass, basin wildrye, Idaho fescue, Sandberg's bluegrass and needlegrasses, which dominate the understory. Invasive annual grasses, such as cheatgrass and medusahead, are invading many sagebrush steppe communities.

Research focus. EOA research builds on a rich history dating from the 1940s. The first objective is to improve understanding of rangeland, riparian, and meadow ecosystems in the northern Great Basin. Within this objective is an emphasis on juniper encroachment, prescribed fire, native seed production, productivity, and carbon sequestration. The second objective is to provide information to develop restoration strategies under forage and livestock management systems. The third objective is to produce management tools and provide information and technology transfer to aid in the restoration and management of public and private rangeland ecosystems dominated or threatened by weed invasion.

Long-term research example. Western juniper woodlands are cut to restore shrub and herbaceous productivity and composition in the northern Great Basin. This study assessed successional dynamics for 12 years following juniper cutting. Total biomass, cover, and density of understory species increased ($p < 0.001$) in cut plots over time and were greater ($p < 0.001$) in cut areas compared to woodland controls (figure A1-22). In the sixth year after cutting (1997), debris and canopy locations were dominated by annual grasses. By 2003, perennial grass biomass was two times greater than annual grass in these zones. Shrub cover and density increased ($p < 0.05$) between 1997 and 2003 in the cut treatment. Densities of perennial grasses have remained stable at 10 plants/m^2 since 1997. These results show that removal of juniper can be an effective long-term management tool to increase perennial grasses in the northern Great Basin.

Figure A1-21. The Eastern Oregon Agricultural Research Center (EOA USDA-ARS) is located in sagebrush steppe and western juniper woodlands. (Photo by Jon Bates.)

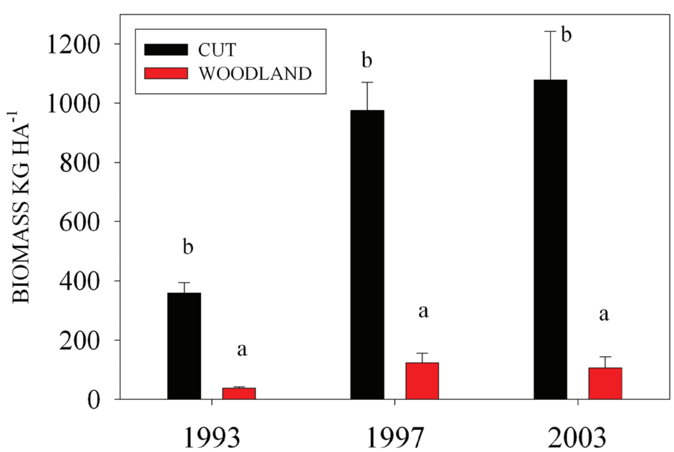

Figure A1-22. Understory biomass was 10 times greater following cutting of juniper (black) controlled with an uncut juniper woodland (red) (modified from Bates et al. 2005). Different lowercase letters indicate significant differences between treatments within a year ($p < 0.01$).

Fernow Experimental Forest (FER) [USFS]

http://www.fs.fed.us/ne/parsons/

The Fernow Experimental Forest (FER) was established in 1934 in West Virginia within the Allegheny Mountain section of the unglaciated Allegheny Plateau. The FER forests were heavily cut over between 1905 and 1911. The current, mostly second-growth, vegetation is classified as a mixed mesophytic forest type (figure A1-23). Characteristic overstory species include northern red oak *(Quercus rubra),* yellow-poplar *(Liriodendron tulipifera),* American beech *(Fagus grandifolia),* black cherry *(Prunus serotina),* sugar maple *(Acer saccharum),* and red maple *(A. rubrum).* Overall diversity of vascular plant species is high, and wildlife is typical of the central Appalachians.

Elevation ranges from 533 to 1,112 m, and slopes are generally steep. The climate is characterized as cool and rainy with precipitation evenly distributed throughout the year. Soils are mostly of the Calvin and Dekalb series, which originated from rocky materials (loamy-skeletal, mixed mesic Typic Dystrudepts).

Research focus. Both silvicultural and hydrologic research are focuses. Silvicultural research addresses questions relating to regenerating, growing, tending, and harvesting trees and stands of mixed hardwoods. Watershed research addresses questions about hydrology and water use by forests, as well as forest management effects on water and soil resources, and about the development of best management practices. The FER has been in the forefront of acid deposition and nitrogen saturation research, conducting a whole-watershed acidification study since 1989. The FER serves as a template for examining wildlife-habitat relationships in managed forests. Recent efforts focus on the role of both natural and anthropogenic forest disturbance as positive and negative influences for sensitive species, due to the presence of the endangered Indiana bat *(Myotis sodalis)* and running buffalo clover *(Trifolium stoloniferum).*

Figure A1-23. The Fernow Experimental Forest (FER USFS) is located in mixed hardwood forests of the Appalachian Mountains. (Photo from FER photo gallery.)

Long-term research example: Big Springs Cave at the FER is a winter hibernacula for the endangered Indiana Bat. Winter bat surveys have been conducted periodically since the early 1950s (figure A1-24). Number of bats was low until 1986, when human entry into the cave was prevented. Numbers have increased considerably and remained stable for the past two decades (C. Stihler, unpublished data), despite forest harvesting activity conducted annually since 1949. Recent research investigates the Indiana bat's day use of live trees and snags for roosting and their foraging habitat.

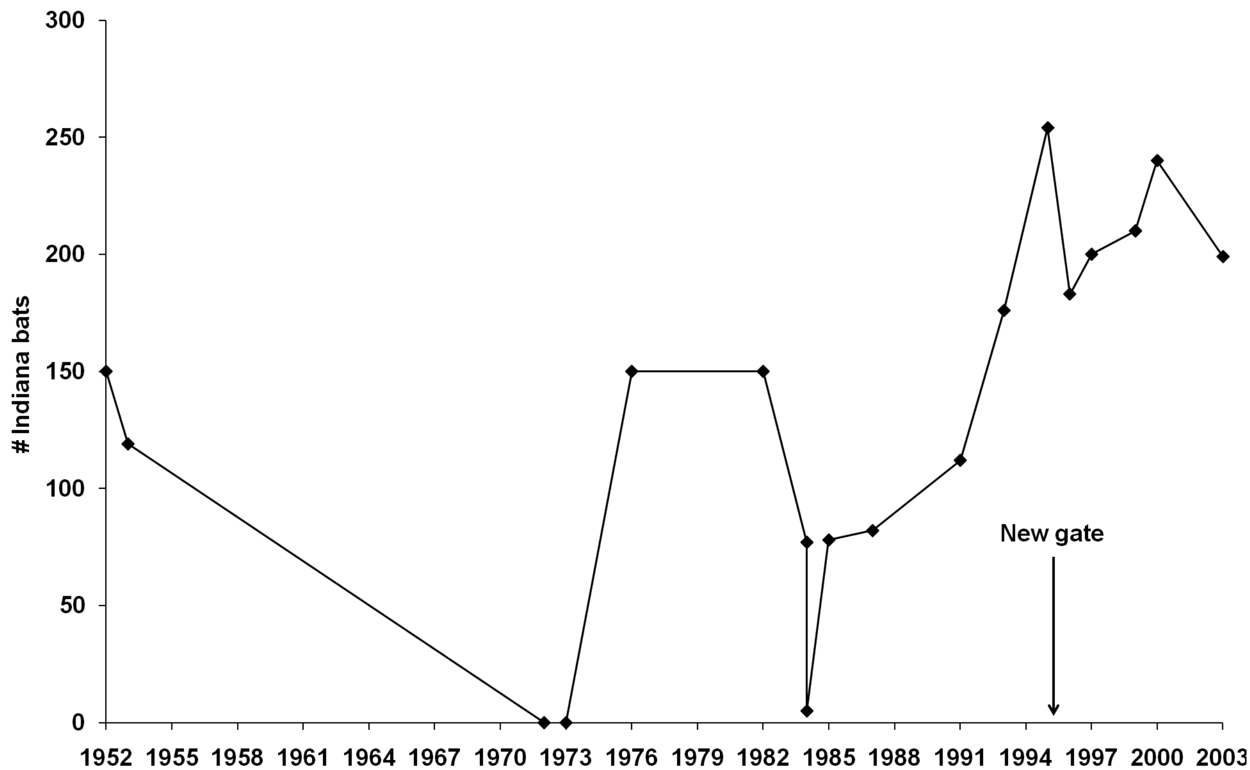

Figure A1-24. Research on hibernating Indiana bats, an endangered species, has been conducted on Fernow Experimental Forest (FER) since 1952. Bat numbers increased and have remained stable following the exclusion of humans from the cave in 1986 (C. Stihler, unpublished data).

Florida Coastal Everglades (FCE) [LTER]

http://fcelter.fiu.edu/

The Florida Coastal Everglades (FCE) LTER site was established in 2000 to determine how population- and ecosystem-level dynamics of the coastal Everglades landscape are controlled by water source, water residence time, and local biotic processes and their relative importance. The FCE is located in south Florida, where a rapidly growing human population of over 6 million live in close proximity to—and in surprising dependence on—the Florida Everglades. The FCE site is entirely within the boundaries of Everglades National Park, the third largest wilderness in the continental United States (figure A1-25). The park covers approximately 6,110 km^2 and is part of the greater Everglades ecosystem, which extends north to Lake Okeechobee and the Kissimmee River.

Figure A1-25. Sampling in the mangrove forest at the Florida Coastal Everglades Long Term Ecological Research (FCE LTER) (Shark River Slough, SRS6). (Photo by Victor Rivera-Monroy.)

The elevation gradient in the Everglades is very small, but significant: Water flows to the estuaries from an elevation of about 2 m at the northern boundary of the park. Because the coastal Everglades cover a large area that is, in effect, topographically flat, it is susceptible to dramatic changes in response to sea level rise. Hurricanes and storms are common, and add "pulse" disturbance features to the slow "press" of rising sea level.

Research focus. FCE research focuses on population and ecosystem dynamics in the oligohaline regions of Taylor Slough and Shark River Slough, where freshwater and estuarine ecosystems meet to form ecotones. Researchers are investigating the hydrologic, climatological, and human drivers that affect oligohaline ecotone dynamics, as well as the processes that regulate biophysical inputs to the ecotone from upstream freshwater Everglades marshes and the estuary proper.

Over the last century, human activity has dramatically altered the Everglades, reducing it to half its original extent and compartmentalizing the remaining system with over 2,500 km of canals and levees. Over 95 percent of the people living in south Florida obtain their drinking water from the shallow Biscayne aquifer, which is recharged in near real time by the Everglades. A primary focus of the Everglades Restoration Project is to return the existing Everglades to a healthy and stable state so that it can continue to provide critical ecosystem services to human populations.

Long-term research example: At the FCE site, total nitrogen (TN) concentration has decreased while total phosphorus (TP) concentration shows no trend with time for two mangrove sites along the Taylor River in the southern Everglades (figure A1-26). High daily and seasonal variability make it difficult to determine directional changes unless many years of data are available. These data demonstrate that phosphorus, the limiting nutrient in the Everglades and downstream Florida Bay, has not increased; yet nitrogen concentrations have decreased in spite of suggestions that freshwater Everglades wetlands are a source of increasing nitrogen in marine ecosystems.

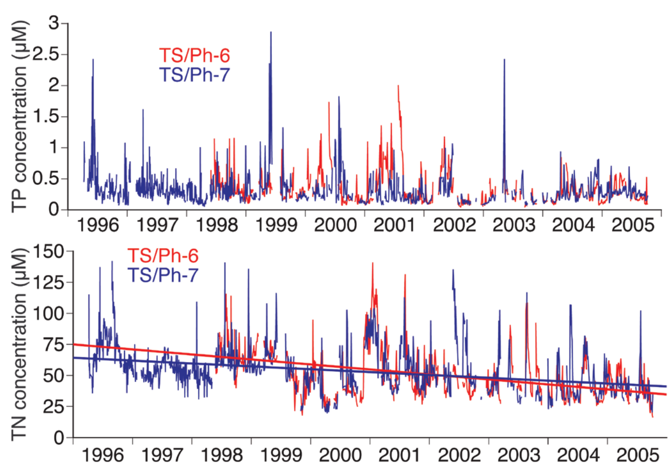

Figure A1-26. (Top) Phosphorous has not changed through time and (bottom) nitrogen has decreased at the Florida Coastal Everglades (FCE) site. (Redrawn from Childers et al. 2006.) Data available at http://fcelter.fiu.edu/data/.

Fort Keogh Livestock and Range Research Laboratory (FTK) [USDA-ARS]

http://ars.usda.gov/

Fort Keogh (FTK) is a USDA Agricultural Research Service facility located west of Miles City, MT. The site was established by Congress as an Army Calvary post on July 22, 1876, approximately 1 month after the Battle of the Little Bighorn. In 1924, Congress transferred FTK to the U.S. Department of Agriculture for agricultural research. Regional topography ranges from rolling hills to badlands with small intersecting streams. The potential natural vegetation is a grama-needlegrass-wheatgrass *(Bouteloua-Stipa-Agropyron)* northern mixed-grass prairie.

FTK currently consists of about 22,700 ha with 20,600 ha of native rangeland, 1,000 ha of seeded dryland pasture, 400 ha of irrigated pasture, and 300 ha of irrigated cropland (figure A1-27). The FTK experimental breeding cow herd consists of about 250 Line 1 Herefords, the oldest and purest line of Herefords in the world; 500 CGC's, a composite gene combination herd consisting of 50 percent Red Angus, 25 percent Tarentaise, and 25 percent Charolais; and 750 mixed-breed cows.

Research focus. The broad mission of FTK is to develop ecologically and economically sustainable range livestock production systems in the face of periodic drought. Current research focuses on developing strategies and decision tools to proactively manage livestock grazing, fire, and drought impacts on the structure and function of mixed-grass prairie while improving animal productivity. In addition, researchers are advancing management strategies to restore rangelands degraded by weeds and to inhibit weed invasions. FTK is also building understanding of the relationships between soil biota and native plants, which should lead to methods benefitting restoration ecology technology.

Figure A1-27. The Fort Keogh Livestock and Range Research Laboratory (FTK USDA-ARS) is located in northern mixed-grass prairie near Miles City, MT. (Photo by Aaron Roth.)

Fraser Experimental Forest (FRA) [USFS]

http://www.fs.fed.us/rm/fraser/

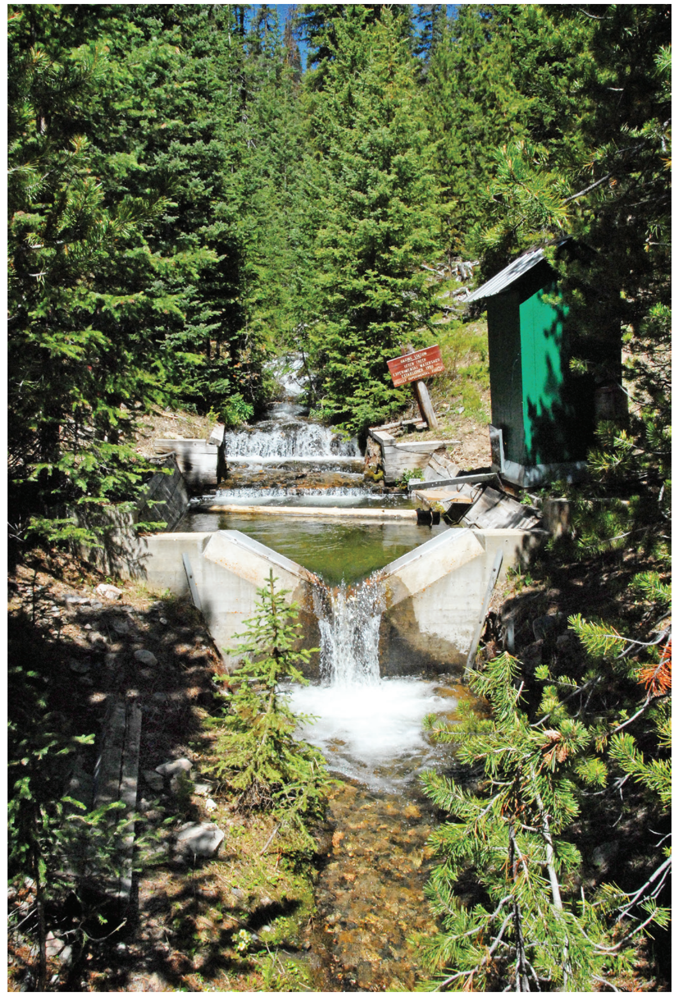

Figure A1-28. The Fraser Experimental Forest (FRA USFS) is located in subalpine coniferous forests of the central Rocky Mountains. (Photo from FRA photo gallery.)

The Fraser Experimental Forest (FRA) was established in 1937 in high-elevation subalpine coniferous forests located about 80 km west of Denver, CO. FRA includes subalpine forests and alpine tundra typical of the central Rocky Mountains (figure A1-28). In the forested areas below timberline, Engelmann spruce *(Picea engelmannii)* and subalpine fir *(Abies lasiocarpa)* are predominant trees at higher elevations, on north slopes, and along streams; lodgepole pine *(Pinus contorta* var. *latifolia)* is the predominant tree at lower elevations and on drier upper slopes.

The majority of the forest began natural regeneration after a stand-replacing fire in 1685. Pockets of older trees exist in draws and at higher elevations. The flat, low-elevation portion of the forest was logged in the early 1900s.

Overall, the climate is cool and humid with long, cold winters and short, cool summers. Frost and snowfall can occur any month of the year. Nearly two-thirds of the precipitation falls as snow from October to May, and about half of the precipitation is lost as runoff with peak flow in the second week of June. Elevation varies from 2,680 to 3,900 m, and about one-third of FRA is above timberline at 3,350 m.

Research focus. The FRA studies effects of management practices on water yield and quality. Long-term study plots were established in both lodgepole pine and Engelmann spruce, and seven watersheds have been monitored for streamflow, climate, and snow; some records now go back more than 60 years. Snow depth and water content are collected on five watersheds, with records dating to 1941 for one watershed. Current research addresses questions about links among forests, riparian areas, and streams in order to better understand mechanisms important in water balance, watershed chemistry, nutrient cycling, and ecosystem carbon storage. The current outbreak of mountain pine bark beetle has shifted focus to impacts of widespread disturbance in subalpine forests on changes in water yield, nutrient cycling, soil processes, sedimentation, and riparian structure.

Long-term studies. Most of the hydrological and silvicultural practices used in managing subalpine forests in the central Rocky Mountains are derived from research done at FRA. Improvements in understanding the factors that control snow distribution and water yield across heterogeneous landscapes have been incorporated into water yield models. Studies of tree water use and ecophysiology have provided a better understanding of the growth dynamics of forests and transpiration water loss; and these dynamics have been incorporated into models to predict the effects of changing climate on forest production and carbon storage. Long-term studies of manipulated forest stands indicate that recovery requires substantially longer than originally hypothesized.

Aquatic and terrestrial biogeochemistry have been studied in manipulated and control catchments, providing a greater understanding of the processes that control stream water quality. Long-term data sets of stream and precipitation chemistry are extremely valuable given the potential for increases in anthropogenic emissions in coming decades.

Georgia Coastal Ecosystems (GCE) [LTER]

http://gce-lter.marsci.uga.edu/

The Georgia Coastal Ecosystems (GCE) LTER program began in 2000 along the central Georgia coast. The study domain encompasses three adjacent sounds (Altamaha, Doboy, and Sapelo) and includes upland (mainland, barrier islands, marsh hammocks), intertidal (fresh, brackish, and salt marsh), and submerged (river, estuary, continental shelf) habitats (figure A1-29). Vegetation is representative of the southeastern coast and includes salt marshes (dominated by salt marsh cord grass, *Spartina alterniflora,* and black needle rush, *Juncus roemerianus*) and maritime forest (dominated by live oak, *Quercus virginiana*) that grade into brackish and fresh marshes and floodplain bald cypress forest.

Patterns and processes in this complex landscape vary spatially within and between sites and temporally on multiple scales (tidal, diurnal, seasonal, and inter-annual). Overlain on these spatial and temporal variations are long-term trends caused by climate change, sea level rise, and human alterations of the landscape (figure 9-3). These long-term trends are manifested in many ways, including changes in water quality, river discharge, runoff, and tidal inundation patterns throughout the estuarine landscape.

Research focus. GCE study sites are distributed along an onshore-offshore gradient across the domain span the full range from tidal fresh to tidal marine habitats. Project objectives are—

- to document long-term patterns of environmental forcing to the coastal zone,
- to link environmental forcing to observed spatial and temporal patterns of biogeochemical processes, primary production, community dynamics, decomposition, and disturbance,
- to investigate underlying mechanisms by which environmental gradients vary longitudinally (freshwater-saltwater) and laterally (upland-subtidal) to drive ecosystem change, and
- to explore the relative importance of larval transport and the conditions of the adult environment for a number of species in determining community and genetic structure across the landscape.

Long-term research example. The Altamaha River is the largest source of fresh water to the GCE domain and provides a natural gradient of freshwater inflow. It drains a watershed of 36,700 km^2 that is relatively undeveloped. Estimates of nitrogen input to the watershed show an increase since 1954 with a peak in 1974 (figure A1-30). Fertilizer tends to be the most important input of nitrogen to the watershed, although net food and feed import increased in importance to become the dominant source by 2002.

Figure A1-29. The Georgia Coastal Ecosystems Long Term Ecological Research site (GCE LTER) consists of upland, intertidal, and submerged habitats. (Photo by Wade Sheldon.)

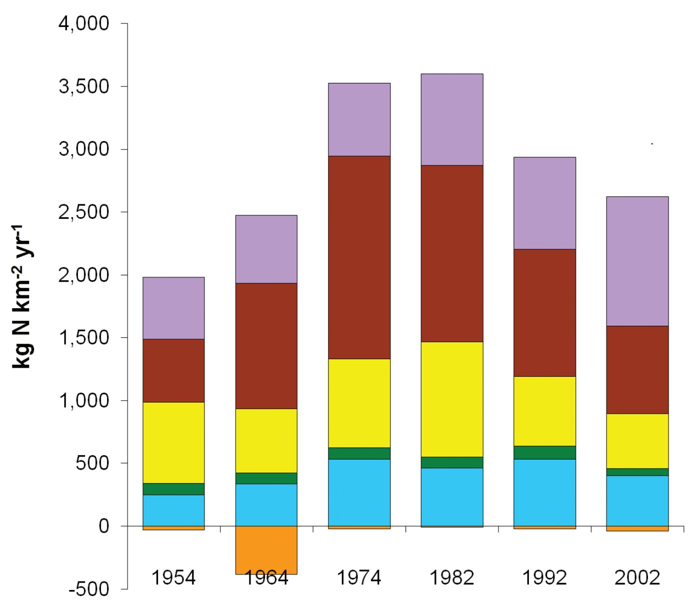

Figure A1-30. Nitrogen inputs to the Altamaha River watershed, over time, in the Georgia Coastal Ecosystems (GCE) site: net food and feed import (lavender), fertilizer input (maroon), biological nitrogen fixation in agricultural lands (yellow), biological nitrogen fixation in forest lands (green), net atmospheric nitrogen deposition (teal), and non-food export (orange). (Redrawn from Schaefer and Alber 2007.)

Glacier Lakes (GLA) [USFS]

http://www.fs.fed.us/rmrs/experimental-forests/glacier-lake-ecosystem-experiments-site/

The Glacier Lakes Ecosystem Experiments Site (GLA) was established in the late 1980s to conduct aquatic and terrestrial studies in high elevation alpine and subalpine ecosystems. The GLA is located at 3,200 to 3,500 m elevation in the Snowy Range in the Medicine Bow Mountains of southeastern Wyoming. The GLA is a 760-ha wilderness-like watershed in complex mountainous terrain containing small alpine to subalpine catchments that include persistent snowfields, glacial cirque lakes, first and second order streams, wetlands, and forest (figure A1-31). The environment is harsh with a short growing season, high winds, and low temperatures.

Figure A1-31. The Glacier Lakes Ecosystem Experiments Site (GLA USFS) includes Lost Lake, a glacial cirque basin along the Snowy Range ridge. (Photo by Robert Musselman.)

Dominant landscape types are alpine, subalpine meadow, Engelmann spruce/subalpine fir forest, shrub, krummholz (wind-deformed conifer trees), exposed bedrock, and scree. Included are old-growth forests with trees more than 700 years old. Most aquatic research is conducted at two adjacent alpine lakes (East and West Glacier Lakes) with similar surface area and depth but differing in catchment area, inflow patterns, turnover rates, stratification, snow cover, deposition of nutrients, water chemistry, and aquatic biota.

Research focus. Current research includes studies of long-term trends in deposition, effects of nitrogen deposition on subalpine meadow and on riparian systems, effects of winter recreation on air quality, the cycling of nitrogen through riparian ecosystems, the dynamics of disturbance in subalpine ecosystems, and the development and testing of techniques for monitoring of Air Quality Related Values (AQRVs) in wilderness ecosystems.

Long-term research example. Research and monitoring are determining the amount of air pollutants deposited in alpine and subalpine ecosystems and the effect of this deposition on the terrestrial and aquatic system components. At West Glacier Lake, nitrogen deposition in precipitation has been variable since 1987, with most deposition occurring from nitrate rather than ammonium (figure A1-32). On average, both nitrate and ammonium concentrations have increased starting in 1989, although these results need to be used with caution because only 2 early years (1987-1988) are available for comparison.

The GLA is a remote area and is considered to be relatively pristine with low amounts of deposition. Thus, these systems are highly sensitive to climate change, air pollutants, and chemical deposition. Long-term physical, chemical, and biological monitoring are needed to determine impacts of changes in atmospheric chemistry on these ecosystems.

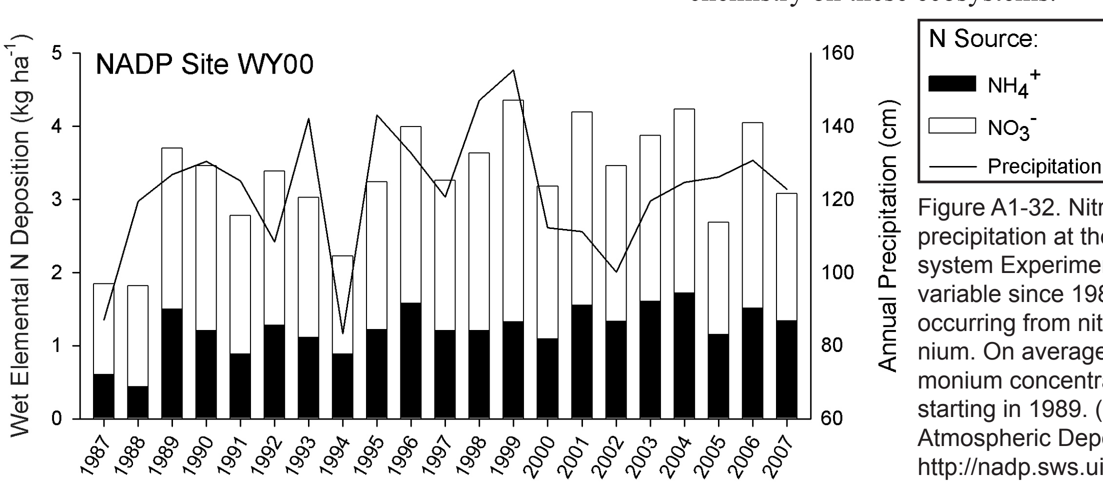

Figure A1-32. Nitrogen deposition in precipitation at the Glacier Lakes Ecosystem Experiments Site (GLA) has been variable since 1987, with most deposition occurring from nitrate rather than ammonium. On average, both nitrate and ammonium concentrations have increased starting in 1989. (Data from National Atmospheric Deposition Program, 2007, http://nadp.sws.uiuc.edu/.)

Grassland, Soil and Water Research Laboratory (GSW) [USDA-ARS]

http://ars.usda.gov/

The Blacklands Experimental Watershed (GSW) was established in 1937 near Riesel, Texas. This experimental watershed facility later became part of the USDA-ARS Grassland, Soil and Water Research Laboratory (GSW). The initial purpose of this watershed and the other two original ARS watersheds (in Coshocton, OH, and Hastings, NE) was to collect hydrologic data (precipitation, percolation, evaporation, runoff, etc.), and to evaluate the hydrologic and soil erosion response of watersheds to agricultural land management practices. The GSW currently contains 340 ha of federally owned and operated land in the heart of the Texas Blackland Prairie, a 4.45 million ha region of fertile agricultural land extending from San Antonio north to the Red River. Present day agricultural use in the region consists of cattle production on pasture and rangeland and corn, wheat, grain sorghum, and oat production.

The Texas Blackland Prairie is known for its Houston Black clay soils, which are commonly recognized as classic Vertisols. Formed from weakly consolidated calcareous clays and marls, these soils are very deep and moderately well drained. The GSW contains several small tracts of remnant (never-plowed) tallgrass prairie dominated by warm-season perennial grasses, including little bluestem and Indian grass, but which also support a diverse mixture of perennial forb species absent from intensively managed grasslands (figure A1-33).

Research focus. Traditionally, research at GSW focused on quantifying hydrologic and soil erosion processes affected by land management. Early research established the soil erosion reduction of conservation practices (terraces, grassed waterways, contour farming, etc.) which provided much of the scientific basis for the American conservation farming revolution. The importance of soil-water phases to temporal runoff patterns in Vertisols was also established. Little runoff occurs in the “dry” soil-water phase, but substantial surface runoff and lateral subsurface return flow occur in the “saturated” phase. This temporal pattern drives the shrink/swell behavior and soil crack formation of Vertisols, which has important implications for the ecology, agriculture, and infrastructure of the region (figure A1-34). Research is also examining the potential effects of changes in rainfall patterns caused by climate change. Rain-exclusion shelters are being used to study effects of altered timing and quantity of precipitation events on forage production and plant species composition on remnant prairies.

Figure A1-33. Remnant tallgrass prairie at the Grassland, Soil and Water Research Laboratory (GSW USDA-ARS) in the Texas Blackland Prairie. (Photo by R. Daren Harmel.)

Figure A1-34. Shrink-swell behavior of Vertisols at the Grassland, Soil and Water Research Laboratory (GSW) results in formation of cracks in the soil, with consequences for ecosystem dynamics, agricultural management, and building and road foundations. (Photo by R. Daren Harmel.)

Grazinglands Research Laboratory (GRL) [USDA-ARS]

http://ars.usda.gov/

The USDA-ARS Grazinglands Research Laboratory (GRL) was established in 1948 on a former U.S. Cavalry remount station. The GRL is located about 45 km west of Oklahoma City, OK, within the central Rolling Red Prairie geomorphic province. The 2,711 ha of land are planted in a variety of forages including: native prairie (1,214 ha), wheat (365 ha), improved grass varieties (809 ha), and numerous experimental plots of cool- and warm-season perennial and annual grasses and legumes (figure A1-35). The most common soil types on GRL are silty-clay loams on crests and side slopes of hills that developed on the Permian-age Dog Creek shale formation. Distribution of precipitation is generally bimodal with peaks in April-May and September-October. Moderate to severe droughts are common and can persist for several years. The frost-free growing season varies from 179 to 249 days, averaging 219 days.

The GRL is near the transition zone between tallgrass prairie to the east and mixed-grass prairie to the west. The prevailing native vegetation is defined as southern tallgrass prairie, often reaching 1 to 3 m in height. Depending on growing conditions, 60 to 90 percent of annual herbaceous production is by warm-season tallgrasses (big bluestem *[Andropogon gerardii],* indiangrass *[Sorghastrum nutans],* and switchgrass *[Panicum virgatum]*), and the mixed-grass little bluestem *(Schizachyrium scoparium)*. The most common perennial cool-season grasses include western wheatgrass *(Elymus smithii),* Canada wildrye *(Elymus canadensis),* and Scribner's panicum *(Panicum oligosanthes)*. Farming within the region is largely dryland with conventional tillage practices the norm, but interest in conservation tillage is increasing.

Research focus. The primary focus of the GRL is control of stocking rate and timing of grazing, use of complementary farmed forages to enhance livestock production, application of prescribed spring burns to control woody species, and control of broadleaf weeds with herbicides.

Long-term studies. Species composition and productivity of southern tallgrass prairie vary in response to management and precipitation. As the dominant tallgrasses and mixed-grasses decline in response to disturbance, they are replaced by less common components of the plant community or invasive perennial grasses. This shift is impermanent, and species composition will generally return to a tallgrass-dominated state with increased precipitation or reduced grazing pressure.

Figure A1-35. Developing integrated crop, forage, and livestock systems under variable climate, energy, and market conditions is a focus of the Grazinglands Research Laboratory (GRL USDA-ARS) near Oklahoma City, OK. (Photo by Michael Brown.)

Harrison Experimental Forest (HAR) [USFS]

http://www.srs.fs.usda.gov/

The Harrison Experimental Forest (HAR) was established in 1934 as a research site for studies of reforestation methods and wood preservation treatments. The forest is located near the Gulf of Mexico in the DeSoto Ranger District of the DeSoto National Forest. The HAR comprises 1,662 ha of forest with soils and topography representative of the longleaf pine forest type that once covered about 12.5 million ha across the Southeastern United States (figure A1-36).

Soils are mostly well-drained, fine-sandy loams of the Ruston and Mclaurin series. Overall, the soils are low in cation-exchange capacity, organic matter, and nutrients and are similar to the lateritic soils of the tropics. The climate is temperate-humid subtropical with precipitation distributed relatively uniformly throughout the year.

Research focus. The mission at the HAR is to provide scientific understanding of the effects of genetics, environment, and their interactions on the function and management of southern forest ecosystems. Species comparisons among the southern pines planted on the HAR as early as the 1950s-1960s have demonstrated species differences in growth trajectories and stand dynamics. Some of the earliest genetic information on longleaf and loblolly pines was generated from plantings consisting of hundreds of control-pollinated families and thousands of trees established by HAR scientists. The HAR has a large collection of southern pine genotypes that serve as a source of germplasm for genetic experiments as well as for gene conservation. Research on the biology and genetics of the southern pine/fusiform rust pathosystem has been conducted. DNA markers are being used to help incorporate blight resistance into the American chestnut, aiding the effort to reestablish this species.

Long-term research. Early research concentrated on southern pine regeneration studies, as well as investigation of various wood preservatives. In 1954, the Southern Institute of Forest Genetics (SIFG) was established shortly after the South-wide Southern Pine Seed Source Study (SSPSSS) was initiated. This study includes 130 individual field experiments at 60 locations (including the HAR) ranging from Texas to Missouri in the west and from Florida to Pennsylvania and New Jersey in the east. These experiments tested growth and survival of 103 seed sources for four major southern pine species. Currently a database is being developed which contains records for 165,696 trees.

Figure A1-36. A longleaf pine and saw palmetto site in the Harrison Experimental Forest (HAR USFS). (Photo from HAR photo gallery.)

Harvard Forest (HFR) [LTER]

http://harvardforest.fas.harvard.edu/

The Harvard Forest (HFR) was established as an LTER site in 1988 to understand historical and modern changes in the landscape of New England and the Northeastern United States resulting from human and natural disturbance processes and to apply this information to the conservation and management of forest ecosystems. Founded in 1907, the HFR is Harvard University's center for field research and education in ecology and conservation. Harvard Forest is one of the oldest and most intensively studied landscapes in North America.

The HFR is located in Petersham, Massachusetts, 65 miles west of Boston. Elevation ranges from 210 to 420 meters. Precipitation is distributed evenly throughout the year. A persistent snow pack forms in most years. Hurricane wind damage at the F1 level (Fujita scale) occurs on average every 20 years. Habitats are typical of central New England and include northern, transition, and central forest types; marshes, hardwood swamps, and conifer bogs; forest plantations; and a 70-acre pond (figure A1-37). At the height of agricultural development (1830-1850), approximately 75 percent of the land was cleared for cultivation or pasture (Foster and Aber 2004).

Figure A1-37. Transition hardwood forests with stone walls from the agricultural past are an important part of landscapes of the Harvard Forest (HFR LTER). (Photo by David R. Foster.)

Research focus. An important goal of HFR research is to examine the drivers of landscape change for human populations and for the diverse natural ecosystems of the Northeast. Drivers range from microbes to moose, invasive plants to exotic insects, hurricanes to forest harvesting, and global climate change to regional land use. Their consequences are explored through paleological and historical studies, regional studies, long-term measurements, modeling, and controlled experimental manipulations—several of which are entering their third decade.

Long-term research example. Changes in forest structure (figure A1-38, top) and composition (figure A1-38, bottom) in southwestern New Hampshire from the early 1900s to 2000 show the forest's response to the 1938 hurricane. The original old-growth forest was composed of widely spaced, but massive, white pine and hemlock, which were nearly all blown down by the storm. A young and dense stand of hemlock, beech, red maple, and birch has been undergoing a process of thinning in density and gradual increase in basal area over the past 70 years. White pine was essentially eliminated from the stand by the storm.

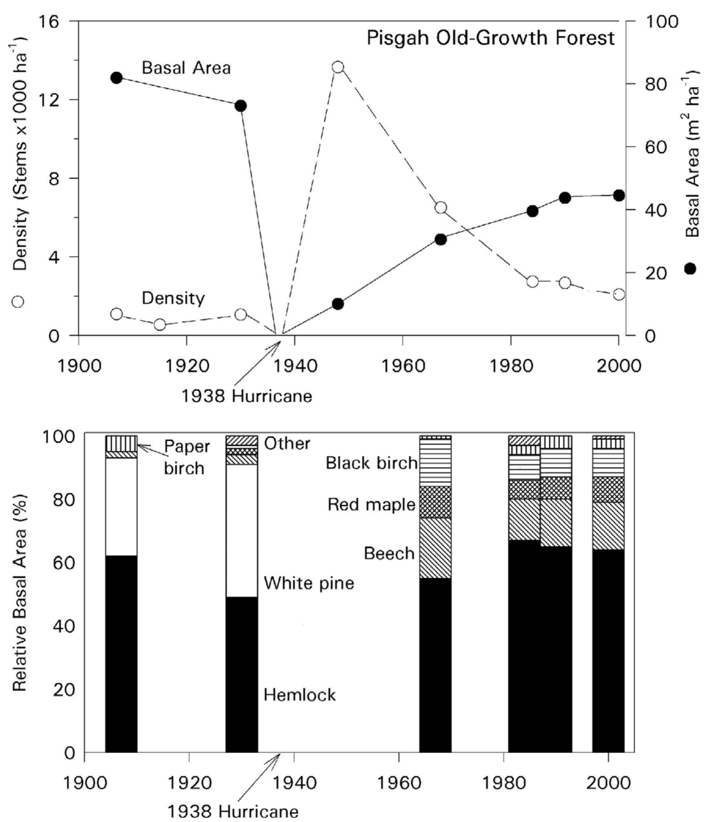

Figure A1-38. Change in density (top) and basal area (bottom) of trees before and after the 1938 hurricane at the Harvard Forest (HFR) (Foster et al. 2004). Reprinted with permission from Yale University Press.

Hubbard Brook Ecosystem Study (HBR) [USFS, LTER]

http://www.hubbardbrook.org/

The Hubbard Brook Ecosystem Study (HBR) was established in 1955 as a center for hydrologic research in New England. The site is located within the White Mountain National Forest in central New Hampshire. The HBR is a 3,160-ha, bowl-shaped valley ranging from 222 to 1,015 m in elevation.

The site is entirely forested, mainly with deciduous northern hardwoods: sugar maple *(Acer saccharum),* American beech *(Fagus grandifolia),* and yellow birch *(Betula alleghaniensis)* (figure A1-39). Red spruce *(Picea rubens),* balsam fir *(Abies balsamea),* and mountain paper birch *(Betula papyrifera* var. *cordifolia)* are abundant at higher elevations and on rock outcrops. Pin cherry *(Prunus pensylvanica),* a shade intolerant species, dominates all sites for the first decade following a major forest disturbance. Logging operations, which ended around 1915-1917, removed large portions of the conifers and allowed growth of better quality, more accessible hardwoods. The present second-growth forest is composed of about 80 to 90 percent hardwoods and 10 to 20 percent conifers.

Research focus. Research at the HBR includes studies of mountain ranges, rivers, lakes, and wetlands that provide habitat for many wildlife species, including moose, pine marten, Canada lynx, song birds, peregrine falcons, and bald eagles (figure 3-4). Critical environmental issues are land development and disturbance, air pollution, climate change, introduced species, water supply and quality, and carbon management.

The small watershed ecosystem approach to nutrient cycling was pioneered at HBR (Bormann and Likens 1985). This method uses the forest ecosystem as a living laboratory in which scientists conduct experiments on an entire watershed and monitor resulting long-term changes in streamflow, nutrient cycling, forest growth, and habitat (figure 5-3). Whole-ecosystem manipulations conducted at HBR include experiments that simulate forest management practices, such as forest clear-cutting, strip cutting, herbicide application and nutrient cation additions, and that provide a scientific basis for improved forest management.

Figure A1-39. The Hubbard Brook Ecosystem Study (HBR USFS/LTER) was established to study hydrologic processes in the northern hardwood forests of the northeastern United States. (Photo from Hubbard Brook Research Foundation.)

Long-term research example: The increase in chloride concentrations at the northeast inlet (green) and Mirror Lake outlet (blue) (figure A1-40) are caused primarily by runoff of road salt used to de-ice Interstate 93, which runs north-south through central New Hampshire (Rosenberry et al. 1999, Kaushal et al. 2005, Likens and Buso 2010). Much of the road salt is transported to Mirror Lake by the northeast inlet stream, which provides only a small portion (2 percent) of the stream flow to the lake but about 30-50 percent of all chloride. Chloride concentrations at the northeast inlet began to increase in 1970 when I-93 opened despite the installation of an earthen diversion dam. The decrease in concentrations in 1995-1996 was likely due to dilution from higher than average precipitation. After 2000, further declines resulted from installation of a plastic liner adjacent to the highway to divert contaminated runoff away from the lake. Chloride concentrations in the lake outlet, unlike those in the northeast inlet, have continued to increase due to increases in the use of salt on local roads which intersect the west and northwest inlets to the lake and contribute 47 percent of the water inflow.

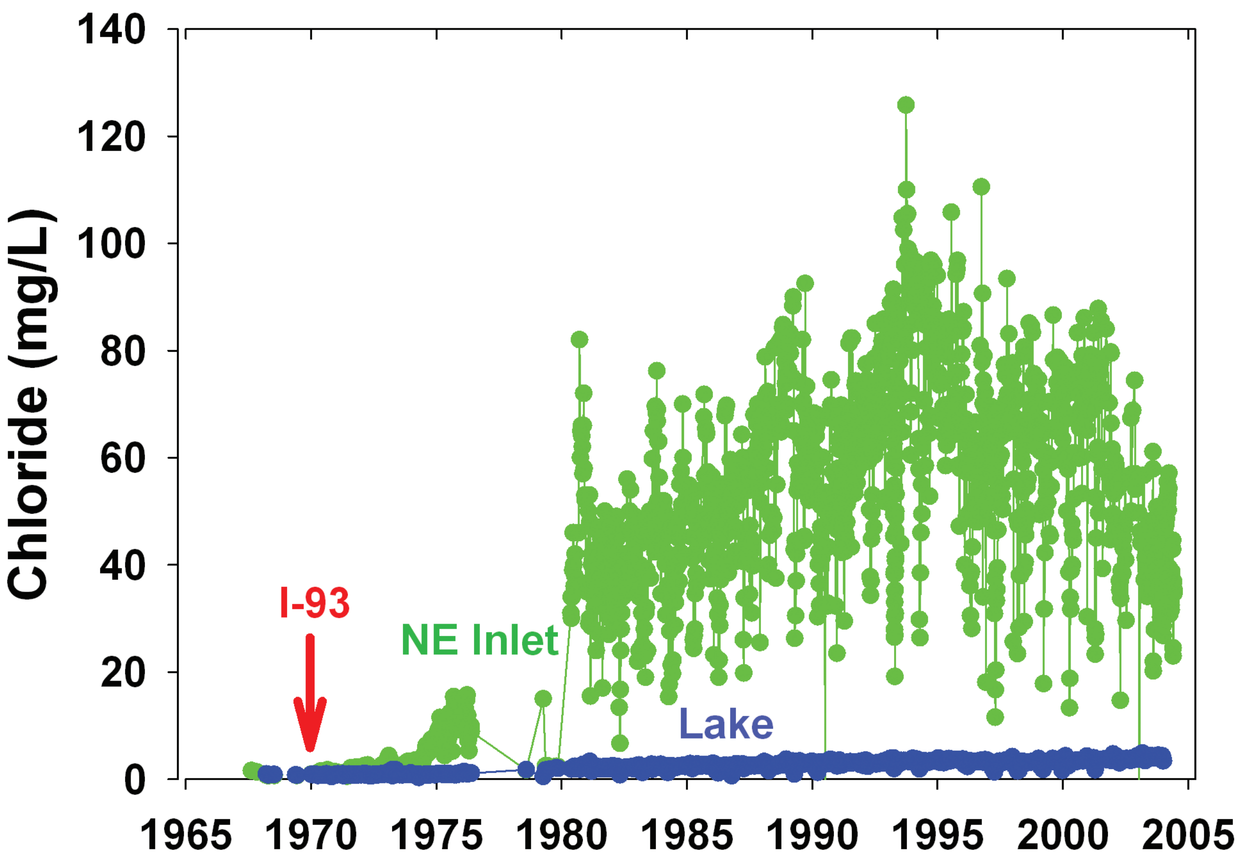

Figure A1-40. The increase in chloride concentrations at the northeast inlet (green) and Mirror Lake outlet (blue) are caused primarily by runoff of road salt used to de-ice Interstate 93, which runs north-south through central New Hampshire near the Hubbard Brook Ecosystem Study (HBR). Change in chloride concentrations through time reflect human activities. (Redrawn from Kaushal et al. 2005; Likens and Buso 2010.)

Jornada (JRN) (USDA-ARS, LTER)

http://jornada-www.nmsu.edu/

The Jornada Basin (JRN) LTER program was established in 1982 to quantify the key factors and processes controlling ecosystem dynamics and patterns in Chihuahuan Desert landscapes. The study site includes the 78,000-ha Jornada Experimental Range operated by the USDA Agricultural Research Service and the 22,000-ha Chihuahuan Desert Rangeland Research Center (CDRRC) operated by New Mexico State University. Data have been collected since 1915, and vegetation records date to the mid-1800s. The JRN is located 37 km north of Las Cruces, NM.

Livestock grazing was historically the predominant landuse in the region, although urbanization has been increasing (figure 9-20). Annual precipitation is low (avg 26 cm/y) and seasonally variable with 52 percent of rain occurring in summer. Extreme droughts are a recurrent climatic phenomenon with profound influence on the vegetation (figure 9-11). Five major plant communities can be found that differ in their degree of desertification: upland grasslands dominated by black grama *(Bouteloua eriopoda)* (figure A1-41 top), lowland grasslands dominated by tobosa *(Pleuraphis mutica)* and burrograss *(Schleropogon brevifolius),* and a series of desertified shrublands, including tarbush *(Flourensia cernua)* on lower piedmont slopes, creosotebush *(Larrea tridentata)* on upper piedmont slopes and bajadas, and honey mesquite *(Prosopis glandulosa)* on the sandy basin floor (figure A1-41 bottom).

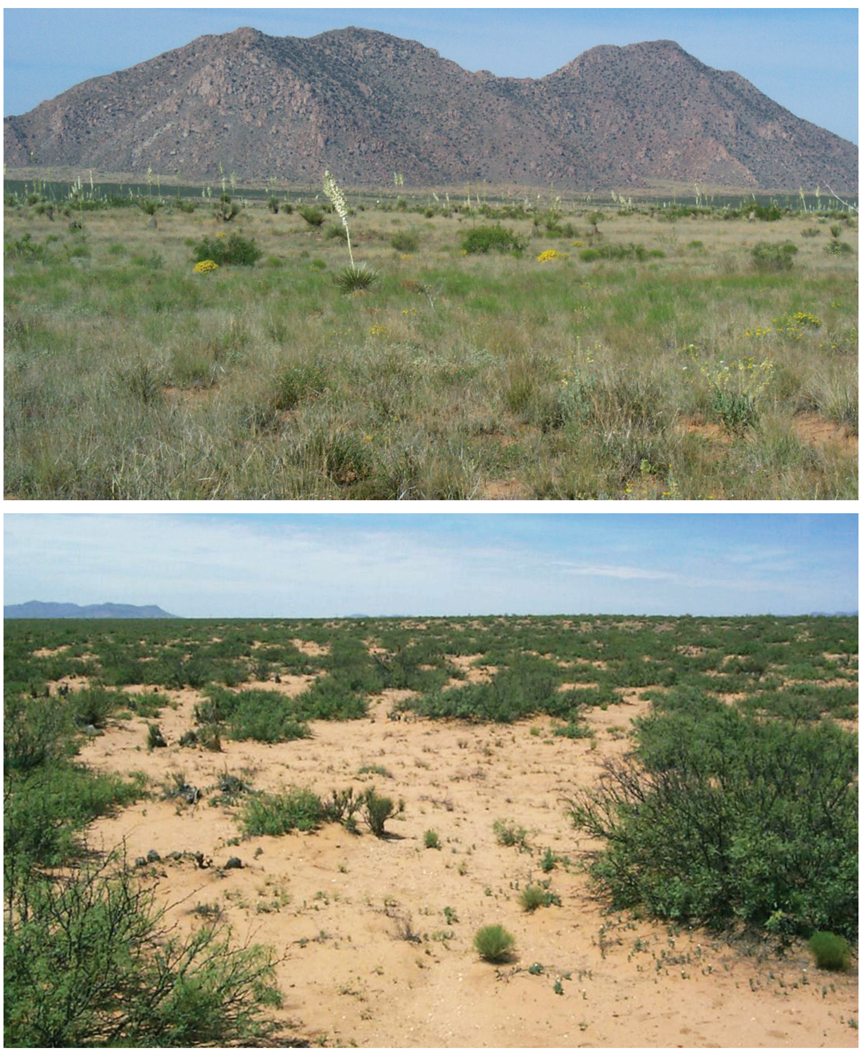

Figure A1-41. The Jornada Basin site (JRN USDA-ARS/LTER) was historically dominated by perennial grasslands (top), though most of the site is now dominated by shrublands such as honey mesquite (bottom). (Photo from JRN photo gallery.)

Research focus. Significant advances in understanding the causes and consequences of desertification have been made at specific spatial scales and for certain environmental conditions (Schlesinger et al. 1990). More recently, the JRN has been investigating the role of spatial and temporal variation in ecosystem properties and processes to desertification dynamics (figure 4-1) and the potential for grass recovery (figure 9-18) (Peters et al. 2004, 2006). Researchers are particularly interested in evaluating how processes interact across a range of scales and under different conditions to drive desertification dynamics and to regulate the conservation of biological resources.

Long-term research example. In general, the amount of area at the JRN dominated by grasslands has decreased from about 80 percent in 1858 to less than 8 percent in 1998, whereas the area dominated by shrubs has increased (figure A1-42). Although the drought of the 1950s has often been implicated as a major driver in the loss of grasses, most of the site was already dominated by shrubs by 1915. Extreme drought and livestock overgrazing in the late 1800s to early 1900s likely led to this shift from grasslands to shrublands at the landscape scale (Fredrickson et al. 1998). Small areas of remnant grasslands remain in 1998; these are often the locations farthest from shrublands early in the 20th century (Yao et al. 2006).

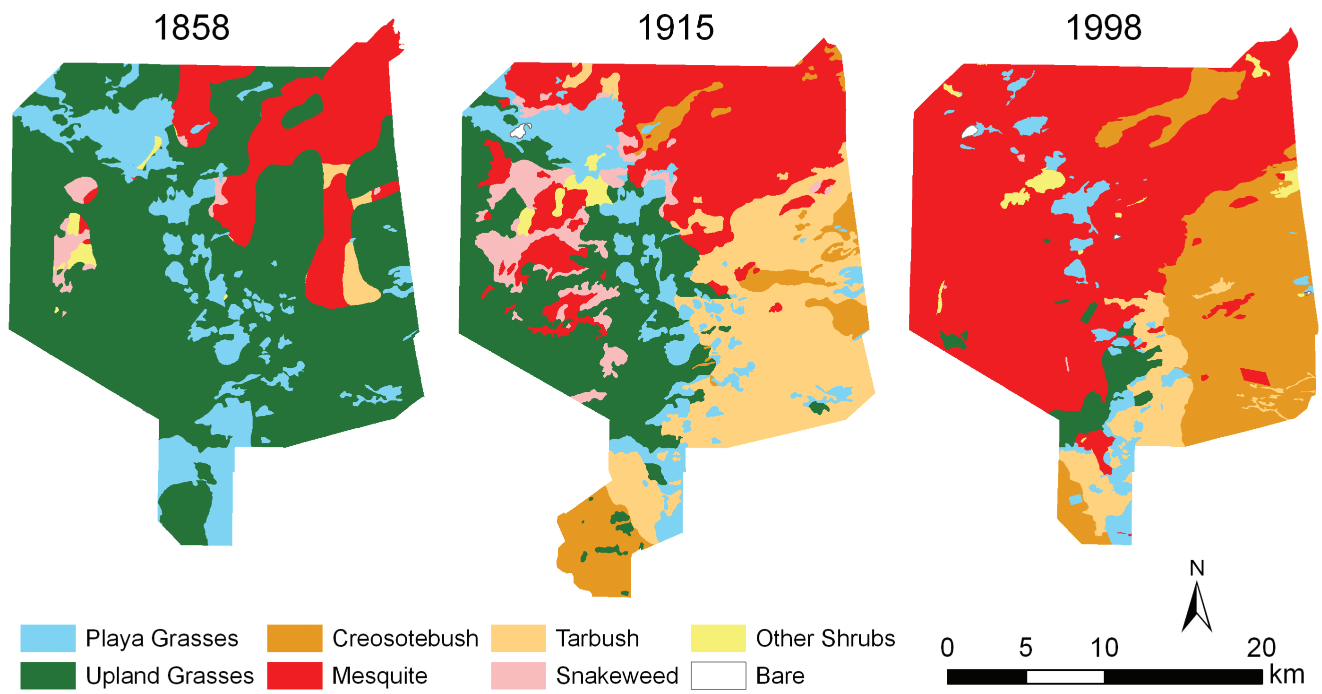

Figure A1-42. Historical maps show that about 80 percent of the Jornada Basin site (JRN) was dominated by perennial grasslands (green, blue) in 1858 but only 8 percent grassland in 1998. Even by 1915, the site was dominated mostly by shrubs (red, tan, brown). (Maps for 1915 and 1998 redrawn from Gibbens et al. 2005.)

Kellogg Biological Station (KBS) [LTER]

http://lter.kbs.msu.edu/

The Kellogg Biological Station (KBS) joined the LTER Network in 1988 to represent intensive row-crop ecosystems, a dominant land use in the U.S. Midwest. KBS consists of 1,600 ha of cropping systems, successional communities, wetlands, and lakes in southwest Michigan. This is in the northeastern portion of the U.S. cornbelt. Land use around KBS ranges from urban (Kalamazoo) to rural. Vegetation ranges from cultivated and early successional old fields to older growth eastern deciduous forest. Aquatic habitats include more than 200 bodies of water within 50 km spanning a wide range of morphometry, geochemistry, and trophic state.

Cropping systems in the area and at KBS are typical of the U.S. cornbelt. Annual crops include corn *(Zea mays),* soybeans *(Glycine max),* and wheat *(Triticum aestivum).* Perennial systems include forage crops such as alfalfa *(Medicago sativa)* and biofuel crops such as hybrid poplar (*Populus* sp.) and switchgrass *(Panicum virgatum)* (figure A1-43). Annual rainfall is evenly distributed seasonally with about half falling as snow. Cropping systems both respond to and influence climate and, in aggregate, play a large role in regional to global biogeochemical cycles. These systems can influence greenhouse gas concentrations in the atmosphere and largely determine nitrate and phosphorus inputs to aquatic systems. Cropping systems also have a large influence on biodiversity and other ecological attributes at local to landscape scales.

Research focus. By understanding how cropping systems function, agronomic management can be adjusted to better utilize biological resources to control pests, provide nitrogen, and build soil fertility, thereby making agriculture more profitable while providing environmental benefits. As such, the goal of KBS research is to develop an improved understanding of ecological interactions underlying the productivity of intensively managed annual and perennial field crops, including corn, soybean, and wheat rotations as well as forage crops such as alfalfa and biofuel crops such as hybrid poplars and switchgrass. Contrasts with unmanaged forest and successional (old field) sites provide important points of comparison for gauging the effects of intensive management on the ecology of organisms in modern field crop ecosystems. An organizing question for KBS research concerns the role of biodiversity in agricultural landscapes and, in particular, the functional significance of diversity with respect to ecosystem function.

Figure A1-43. The Kellogg Biological Station (KBS LTER) studies ecological interactions underlying the productivity and environmental performance of field, forage, and biofuel crops in heterogeneous landscapes. (Photo from KBS photo gallery.)

Long-term research example. As more than half of the conterminous U.S. land base is used for agriculture, relatively minor changes in soil carbon storage or greenhouse gas production from crop fields can have enormous impact when played out over millions of hectares. Field crop agriculture plays a key role in greenhouse gas emissions through practices such as nitrogen fertilizer application and soil tillage. Nitrous oxide (N_2O) and methane (CH_4) are especially important greenhouse gases influenced by agriculture. Methane uptake—the removal of CH_4 from the atmosphere by soil microbes—is inhibited by agriculture (figure A1-44, top, gray bars) to a fraction of that in mature forest (figure A1-44, top, black bars). When the forest is cleared for agriculture, methane uptake is suppressed, allowing more methane to accumulate in the atmosphere than prior to clearing. In contrast, N_2O production is stimulated by agricultural treatments (figure A1-44, bottom), providing a direct source of this greenhouse gas to the atmosphere. Neither change is desirable from a climate-change perspective, but both may be mitigated by appropriate agricultural management, an active area of research at KBS. In these experiments, annual crops were managed as conventional cropping systems, as no-till systems, as low-chemical-input systems, or as organic systems (no fertilizer or manure). Midsuccessional systems were either never tilled (Mid NT) or historically tilled (Early and Mid HT) before establishment.

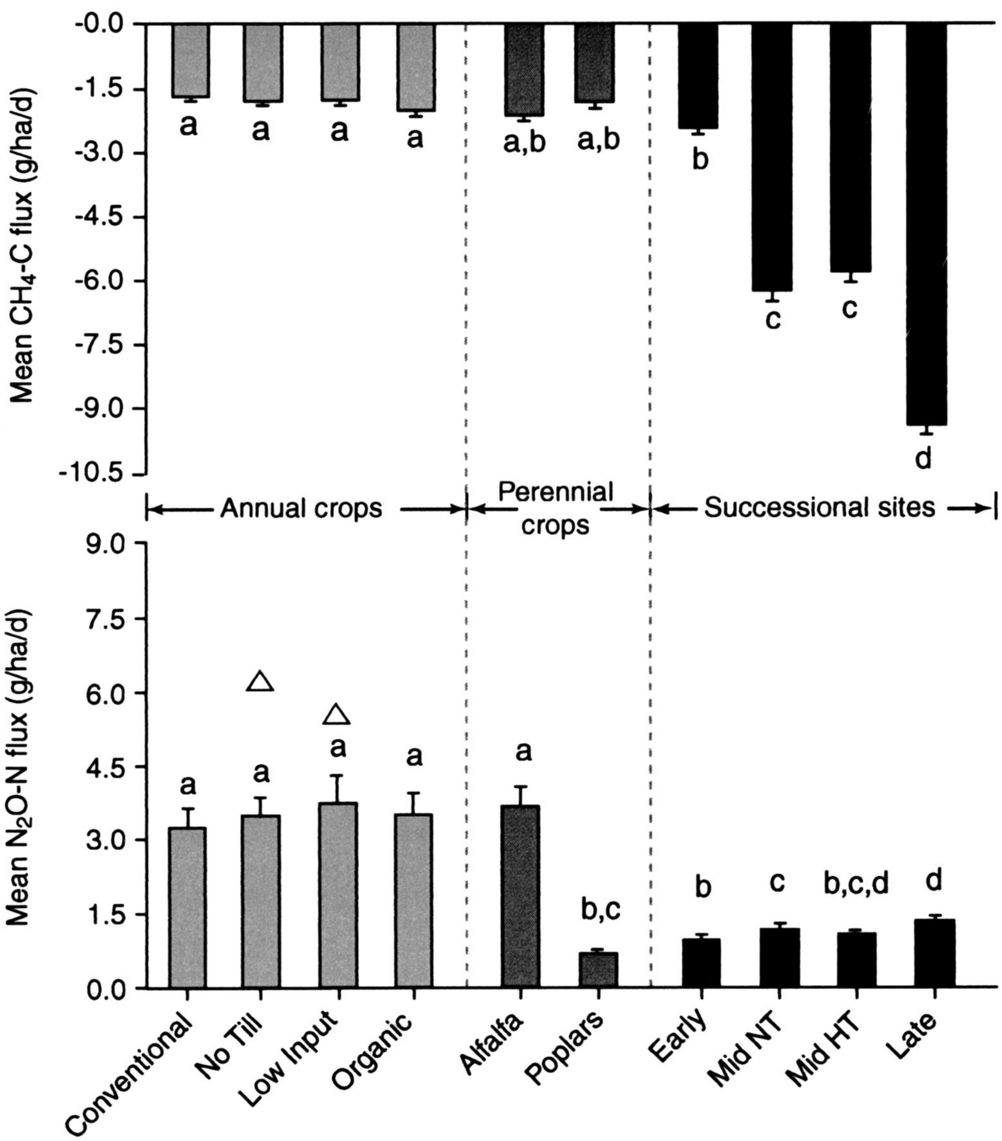

Figure A1-44. Methane oxidation and nitrous oxide production in different cropping systems at the Kellogg Biological Station (KBS) (Robertson et al. 2000). Fluxes were measured over the 1991-1999 period. Methane uptake inhibited by agriculture is indicated by the gray bars at the top of the figure. The black bars at the top represent methane uptake in mature forest. The bottom portion shows N_2O production as stimulated by agricultural treatments. There are no significant differences ($p < 0.05$) among bars that share the same letter. Triangles indicate average fluxes when the single day of anomalously high fluxes in the no-till and low-input systems in 1999 and 1991, respectively, is included. Reprinted with permission from AAAS.

Konza Prairie Biological Station (KNZ) [LTER]

http://www.konza.ksu.edu/

The Konza Prairie (KNZ) LTER program began in 1982 with a focus on fire, grazing, and climatic variability as three key drivers that affect ecological pattern and process in tallgrass prairies worldwide. The focal site for the KNZ program is the 3,487-ha Konza Prairie Biological Station (KPBS) (figure A1-45), a C_4-dominated grassland with a continental climate characterized by warm, wet summers and dry, cold winters.

KPBS is located in the Flint Hills region of northeastern Kansas, an area of steep slopes overlain by shallow limestone soils unsuitable for cultivation. These soils overlay as many as 10 distinct layers of alternating limestone and shale, contributing to the complex subsurface hydrology of the region. Because mean annual precipitation is sufficient to support woodland or savanna vegetation, periodic drought, fire, and grazing are important in maintaining the grassland. The vegetation is primarily (over 90 percent) native tallgrass prairie dominated by perennial C_4 grasses, such as *Andropogon gerardii, Sorghastrum nutans, Panicum virgatum,* and *A. scoparius.* Numerous subdominant grasses, forbs, and woody species contribute to its high floristic diversity. Gallery forests dominated by *Quercus* spp. and *Celtis occidentalis* grow along major stream courses.

Research focus. The KNZ program addresses major abiotic drivers (climate and fire) as well as the numerous biotic interactions (herbivory, competition, mutualism, predation) that shape mesic grassland ecosystems (figure 9-12). The KNZ program features long-term studies and experiments including a replicated watershed-level experiment, in place since 1977, which explicitly incorporates the major factors influencing mesic grasslands in a long-term experimental setting.

Figure A1-45. Konza Prairie Biological Station (KNZ LTER) is located in northeastern Kansas. Vegetation is tallgrass prairie on steep slopes unsuitable for cultivation. Fire is an important management tool to maintain grassland and limit invasion by woody plants. (Photo by Alan K. Knapp.)

Long-term research example. Woody plants have increased through time at the KNZ. GIS (geographic information system) representation has been used to show gallery forest expansion, digitized from aerial photographs from 1939, 1950, 1969, 1985, and 2002. From 1939 to 2002, the extent of the gallery forest increased from 162 ha to 274 ha (figure A1-46). Major drainage boundaries at the Konza Prairie Biological Station are outlined in black in figure A1-46; some of the major streams are outlined in blue. Both fire and livestock grazing are important in limiting woody plant expansion.

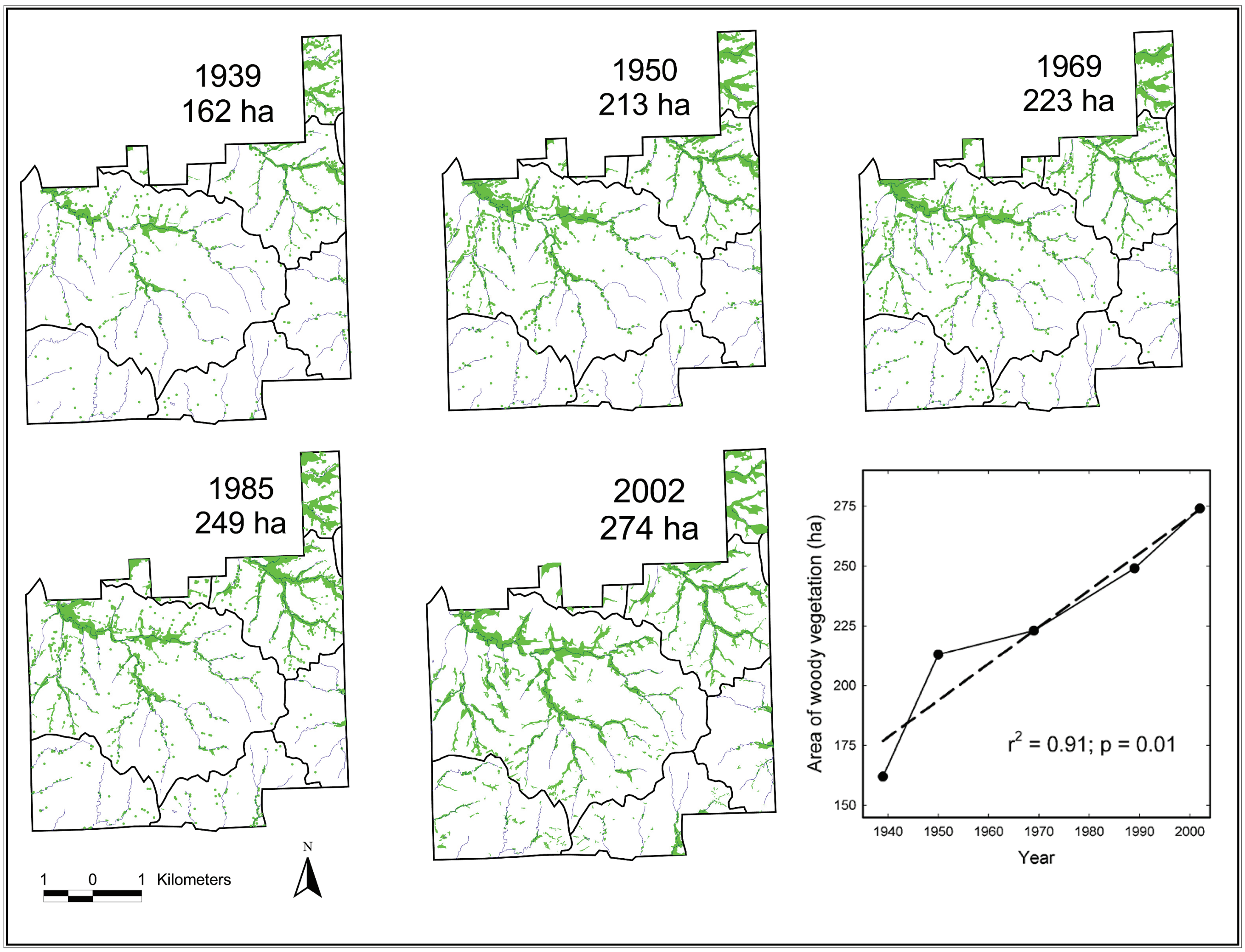

Figure A1-46. Gallery forests increased from 1939 to 2002 at the Konza Prairie Biological Station (KNZ) (Briggs et al. 2005; updated from Knight et al. 1994). Both fire and grazing are critical in maintaining grasslands and limiting woody plant expansion in tallgrass prairie. Reprinted with permission from the American Institute of Biological Sciences.

Loch Vale Watershed (LVW) [USGS]

http://www.nrel.colostate.edu/projects/lvws

Loch Vale Watershed (LVW) is a 660-ha alpine/subalpine catchment located entirely within Rocky Mountain National Park in Colorado. Biogeochemical, hydrologic, and biological information has been collected from Loch Vale since 1983. Because Loch Vale is located in a national park, it has minimal disturbances directly caused by humans. Climate is characterized by long, cold winters and a short growing season of 3-4 months. More than 65 percent of annual precipitation comes as snow between November and June. Approximately 75 percent of precipitation is lost as discharge. The western boundary of the watershed is the continental divide; streams drain northeast. The two main tributaries in Loch Vale, Andrews Creek and Icy Brook, join above The Loch which is the lowest of four lakes in the watershed. The Loch is below treeline, and Sky Pond, Glass Lake, and Andrews Tarn are alpine tarns.

Eleven percent of the catchment is tundra, located primarily on ridgetops (figure A1-47). Old-growth Engelmann spruce/subalpine fir forest is located on the valley bottom and makes up only 6 percent of the land cover. Alpine soils support plant communities largely dominated by lichen, herbaceous vegetation, grasses, and low shrubs. Tundra and wetland soils have pH values around 4.5, while forest soils have pH values between 3.8 and 4.0. Base saturation is greater than 40 percent.

Research focus. Research explores questions related to the role of climate and atmospheric deposition, primarily of nitrogen, in influencing biogeochemical fluxes. Research also explores alpine and subalpine ecosystem dynamics, including vegetation, soil, and water. Paleolimnological research conducted in Sky Pond has yielded insight into changes over time related to climate since deglaciation and into atmospheric deposition of nitrogen, metals, and persistent organic compounds. The overall program objectives are to share results and information on real and potential threats to natural alpine and subalpine resources with the public; scientific community; and air, water, and land managers and to offer a program of graduate education and research that develops future scientists and knowledgeable resource managers.

Figure A1-47. The Loch Vale Watershed (LVW USFS) is an alpine/subalpine site located in Rocky Mountain Park northwest of Denver, CO. More than 80 percent of Loch Vale is made up of exposed bedrock, talus, or glacier. (Photo by David M. Swift.)

Luquillo Experimental Forest (LUQ) [USFS, LTER]

http://luq.lternet.edu/

The Luquillo Experimental Forest (LUQ) was established as an LTER site in 1988 to study tropical forests and streams in Puerto Rico. Research in this area dates back over 100 years, with LUQ being one of the most intensively studied tropical forests in the world. The site is located in the Luquillo Mountains, which harbor the largest area of primary forests and the most pristine rivers in Puerto Rico.

Climate is subtropical maritime moderated by trade winds that maintain relatively constant air temperatures year round. Rainfall is in excess of 100 mm each month, although there are periods of lower rainfall between February and April and higher rainfall in September. Severe hurricanes occur on average every 60 years. These hurricanes and other storms dramatically change forest conditions (figure A1-48; see also figures 9-2, 9-8, 9-9, and 9-10). Drought (less than 100 mm/month) recurs on decadal scales.

Dominant soils are deep, highly weathered and leached clays with low pH and base saturation less than 35 percent at 1.25 m. Soil oxygen decreases with increasing elevation, from 21 percent in aerated soils to anaerobic soils in the highest elevation forests. The vegetation is evergreen broadleaf subtropical forest. The 240 tree species form different forest types with different species composition, structure, and dominance with elevation.

Research focus. The goal of the LUQ is to understand the long-term dynamics of tropical forest and stream ecosystems characterized by a variety of natural and human disturbances, rapid processing of organic material, and high habitat and species diversity. Natural disturbance includes hurricanes, landslides, floods, and droughts (Brokaw et al. 2012). The impact of hurricanes is large, but the organisms are generally resistant and resilient to these storms. The LTER program also studies land-water interactions to understand the role of terrestrial vegetation and land cover on stream fauna and functioning and to determine the capacity of streams to deliver ecological services to urban populations. Human disturbance includes changes in land use and land cover, changes in the atmosphere and climate, and introduction of alien species. Forest cover on the island was reduced to about 5 percent in 1950, but with industrialization and abandonment of agriculture, forests have since recovered.

Figure A1-48. The Luquillo Experimental Forest (LUQ USFS/LTER) in Puerto Rico is an evergreen broadleaf subtropical forest influenced by hurricanes and other storms. (Photo by Jerry Bauer.)

Long-term research example. Litterfall and fruitfall show the effects of multiple hurricanes (figure A1-49). In 1989, Hurricane Hugo struck the site (the first major hurricane since 1932), and afterwards several other hurricanes also affected LUQ. Litterfall (red line) peaks during hurricanes, declines sharply as trees releaf, and soon recovers to prestorm levels. During this recovery, fruit production (black bars) is low, forcing frugivores to move to other locations. Recovery, a measure of resilience, was different for different hurricane events. Hurricane Hugo had the highest pulse of litterfall and the longest period for recovery of fruitfall.

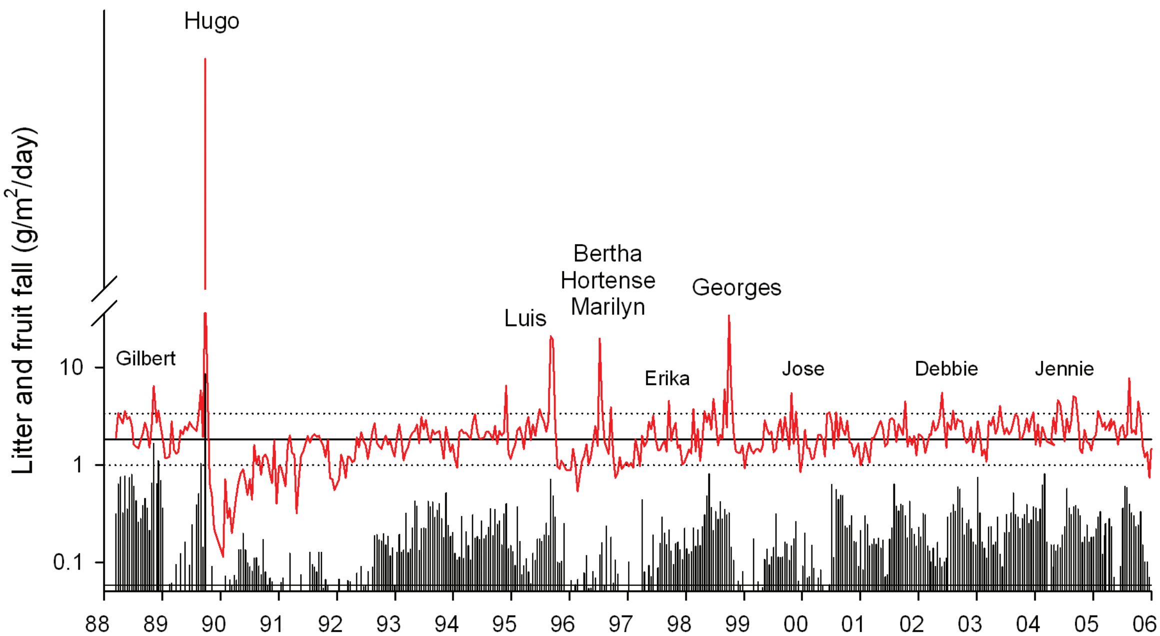

Figure A1-49. Litterfall (red line) and fruitfall during and following multiple hurricanes at the Luquillo Experimental Forest (LUQ). Horizontal solid and dotted lines are mean pre-Hurricane Hugo litterfall rate ± 95 percent CI. Litterfall peaks during hurricanes and declines through time, whereas fruit production (black bars) is low during recovery. (Updated from Scatena et al. 1996.)

Marcell Experimental Forest (MAR) [USFS]

http://nrs.fs.fed.us/ef/locations/mn/marcell/

The Marcell Experimental Forest (MAR) was established to study the ecology and hydrology of lowland watersheds that include peatland, riparian, and upland forests. The MAR is a 1,123-ha tract 40 km north of Grand Rapids, MN. The climate is subhumid continental, with wide and rapid diurnal and seasonal temperature fluctuations. Mineral soils are derived from glacial processes that occurred during the Wisconsin Glaciation, which ended about 10,000 years ago. Organic soil properties reflect peatland hydrology, vegetation, and biogeochemical processes (figure A1-50).

Vegetation varies across the site depending on forest management practices and soil properties. Canopy vegetation in uplands consists of aspen (*Populus tremuloides*, *P. grandidentata*); northern hardwoods; and conifers including white (*Pinus strobus*), red (*Pinus resinosa*), and jack pines (*Pinus banksiana*), balsam fir (*Abies balsamea*), and white spruce (*Picea glauca*). Forested peatlands consist of black spruce (*Picea mariana*), eastern larch (*Larix* sp.), and white cedar (*Thuja occidentalis*).

Research focus. Monitoring of streamflow, weather, and water table elevation began during 1960 and continues to the present. Six watersheds were instrumented to study hydrology. Over the past five decades, watersheds have also been used to study nutrient biogeochemistry, mercury cycling, trace gas emissions, peatlands ecology, and effects of climate change. Effects of timber harvest, prescribed burning, forest fertilization, herbicide use, cattle grazing, and atmospheric deposition on water yield and quality are also studied using large-scale watershed manipulations. These studies provide data that has been used to develop and evaluate Best Management Practices for forest and water resources in lowland watersheds.

Figure A1-50. Marcell Experimental Forest (MAR USFS) is a peatland site in Minnesota where hydrologic studies are conducted. (Photo by E. S. Verry.)

Long-term research example. Groundwater recharge rates have been calculated using long-term measurements of groundwater table elevation (figure A1-51). When snow accumulates on the land surface, ground water recharge ceases during winter and the water table drops due to aquifer drainage. When groundwater table recession during winter is compared to periods of recharge due to rainfall or snowmelt, ground water recharge can be calculated (Nichols and Verry 2001). When recharge values are combined with measurements of streamflow, soil water moisture, and precipitation, the data can be used to define the types and magnitude of hydrological processes that control the storage and transport of water and the implications for water and forest management throughout the region.

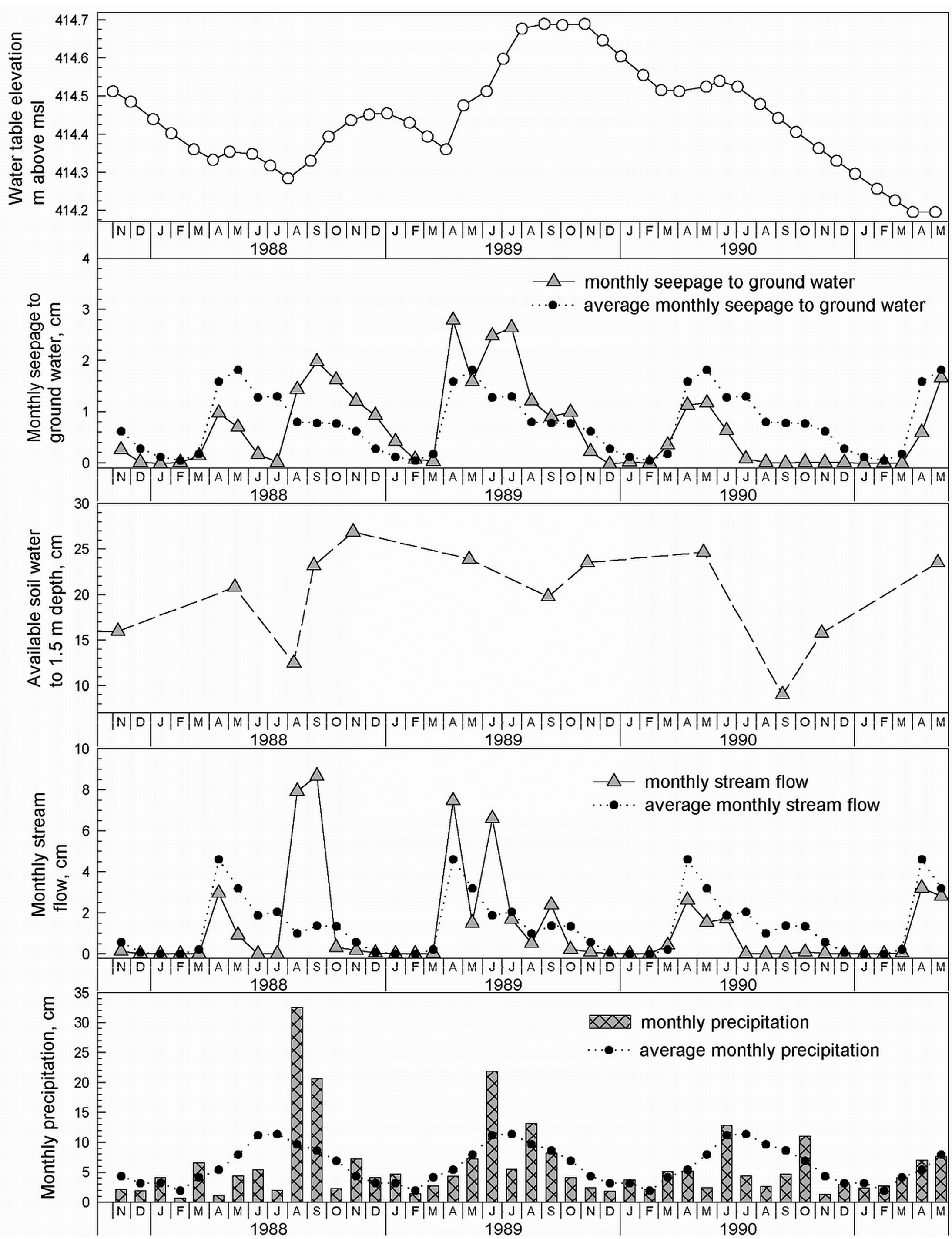

Figure A1-51. At the Marcell Experimental Forest (MAR), various components of hydrological processes are monitored, including ground water recharge (calculated from water table elevation), available soil moisture, streamflow, and precipitation (from watershed 2 during 1988-1990) (Nichols and Verry 2001). Reprinted with permission from Elsevier.

McMurdo Dry Valleys (MCM) [LTER]

http://www.mcmlter.org/

The McMurdo Dry Valleys (MCM) was established as an LTER site in 1993 to study the aquatic and terrestrial ecosystems in an ice-free region of Antarctica. The site is adjacent to McMurdo Sound, 3,500 km south of New Zealand. The area is characterized by a strong solar cycle with continuous sunlight persisting for about half the year followed by 24-hour darkness of polar night. The dry valleys are a mosaic of perennially ice-covered closed-basin lakes, ephemeral streams, bare soils, and glaciers (figure A1-52). A hydrological continuum exists in the dry valleys, beginning with glaciers and ending in closed-basin lakes. Glaciers cover about one-third of the dry valleys. These large reservoirs of water are released through melting and are the only significant source of water to the ephemeral streams and ice-covered lakes. Soils account for the majority of the valley surface area and are generally poorly developed, coarse textured, and high in soluble salts. Soils also support low rates of biological activity by dominant microorganisms. The most complex life forms are small invertebrates. The majority of soils support up to three invertebrate taxa (tardigrades, rotifers, nematodes), but there are regions, in contrast to lower latitude ecosystems, that completely lack soil invertebrates. Aeolian transport is thought to play an important role in the dispersion of soil organisms in the dry valleys.

Research focus. The overall objectives of MCM are to understand the influence of climate legacies on the structure and function of the dry valley ecosystem and to determine the role that contemporary material transport has in structuring this ecosystem.

Long-term research example. Regional climate cooling over the 1990s resulted in alterations of soil invertebrate communities, including changes in diversity and abundance. The abundance of the dominant nematode species, *Scottnema lindsayae,* declined by 114 individuals per kilogram of soil per year at Lake Hoare and by 508 individuals per kilogram of soil per year at Lake Fryxell (Barrett et al. 2008) (figure A1-53). Given the low diversity and long generation times, these declines in population represent important shifts in the diversity, life cycles, trophic relationships, and functioning of dry valley soils.

Figure A1-52. McMurdo Dry Valleys (MCM LTER) is located in the ice-free region of Antarctica and consists of a mosaic of closed-basin lakes, ephemeral streams, bare soils, and glaciers. (Photo by Kathy Welch.)

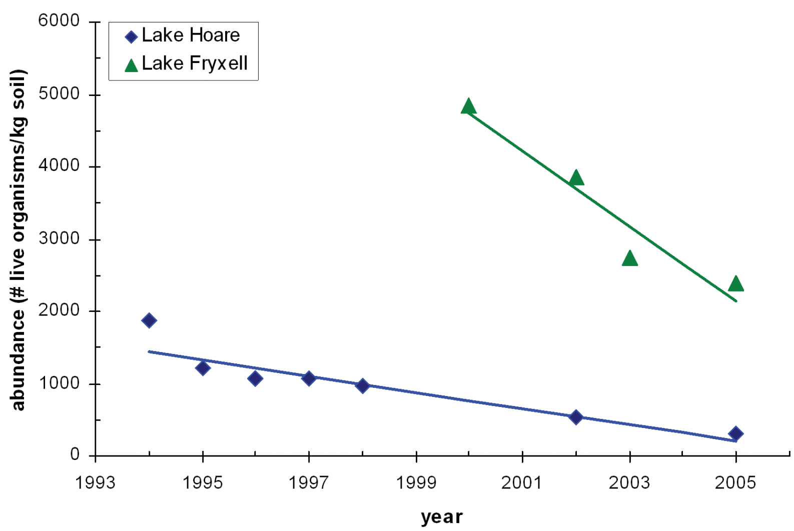

Figure A1-53. Decline in populations of the dominant animal, the nematode *Scottnema lindsayae*, at two lakes in Taylor Valley at the McMurdo Dry Valleys (MCM): Lake Hoare and Lake Fryxell. (Redrawn from Barrett et al. 2008.)

Moorea Coral Reef (MCR) [LTER]

http://mcr.lternet.edu/

The Moorea Coral Reef (MCR) LTER program was established in 2004 to provide a greater understanding of the physical and biological processes that modulate coral reef ecosystem function, shape community structure and diversity, and determine the abundance and dynamics of constituent populations. The site is a complex of coral reefs and lagoons that surround the island of Moorea in French Polynesia in the South Pacific (figure A1-54).

Moorea is a small (perimeter about 60 km) volcanic island 20 km west of Tahiti. Major coral reef types (fringing reef, lagoon patch reefs, back reef, barrier reef, and fore reef) are easily accessible to researchers. Reefs are dominated by massive *(Porites),* branching *(Pocillopora, Acropora),* and encrusting *(Montipora)* coral that are periodically disturbed by cyclones (1982, 1991, 2010), outbreaks of crown-of-thorns sea stars that consume coral (1991, 2008) (figure 9-17), and coral bleaching events (1991, 1994, 2002, 2003). Like coral reefs worldwide, reefs in Moorea are highly vulnerable to ocean warming and ocean acidification.

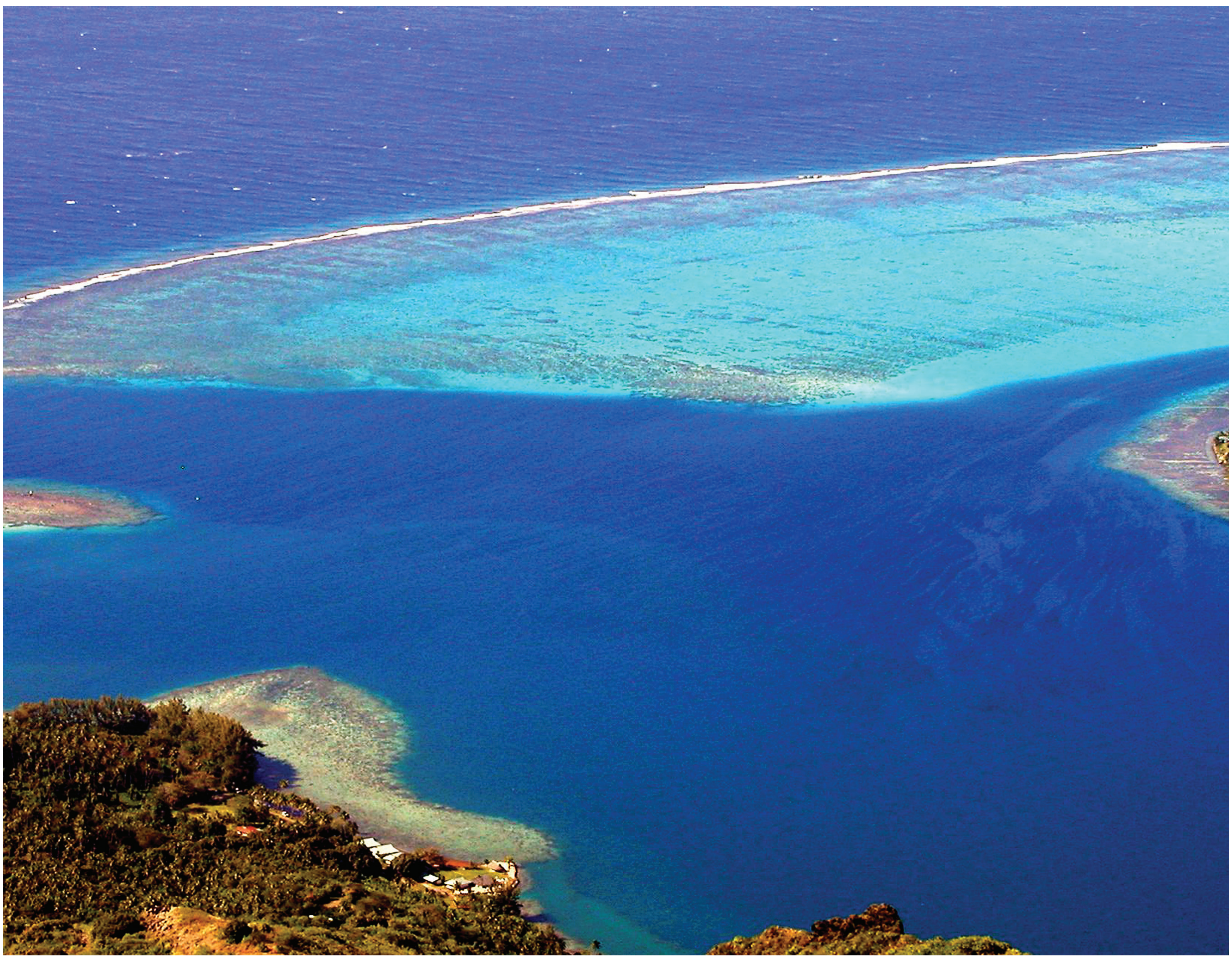

Figure A1-54. The Moorea Coral Reef (MCR LTER) site is a complex of coral reefs and lagoons surrounding the island of Moorea in French Polynesia. (Photo from MCR photo gallery.)

Research focus. The MCR research program focuses on improving understanding of the long-term consequences of disturbance and changing climate regimes on coral reef ecosystems. Principal scientific goals include—

- elucidating the mechanistic basis of oceanographic effects on coral reefs,
- evaluating mechanisms and effects of climate forcing,
- examining how species interactions affect growth, survivorship, and dynamics of corals and other associated organisms,
- exploring food web relationships and nutrient dynamics, and
- understanding the ecological controls and functional significance of biodiversity.

Long-term research example. Long-term data at MCR have challenged longstanding ideas that population dynamics of coral reef fishes can be driven by a highly variable supply of larval colonists that typically is not sufficient to saturate resources. Time series data by MCR researchers reveal a strong influence of habitat limitation on the population size of adult three-spot dascyllus *(Dascyllus trimaculatus).* The density of adult-stage dascyllus tripled over a 14-year period, which represents about two or three complete population turnovers of this fish species (figure A1-55 top) despite order-of-magnitude fluctuations in larval settlement from year to year that had no systematic trend (not shown). Increases in adult fish densities mirrored increases in abundance of the giant sea anemone *Heteractis magnifica* (figure A1-55 bottom), which functions as the settlement habitat for larval colonists and subsequently as nursery habitat for juvenile three-spot dascyllus. Fluctuations in settlement are strongly filtered by density-dependent mortality in the juvenile phase of sea anemones (Schmitt and Holbrook 2000, 2007), which results from competition with predators for space (Holbrook and Schmitt 2002, Schmitt et al. 2009).

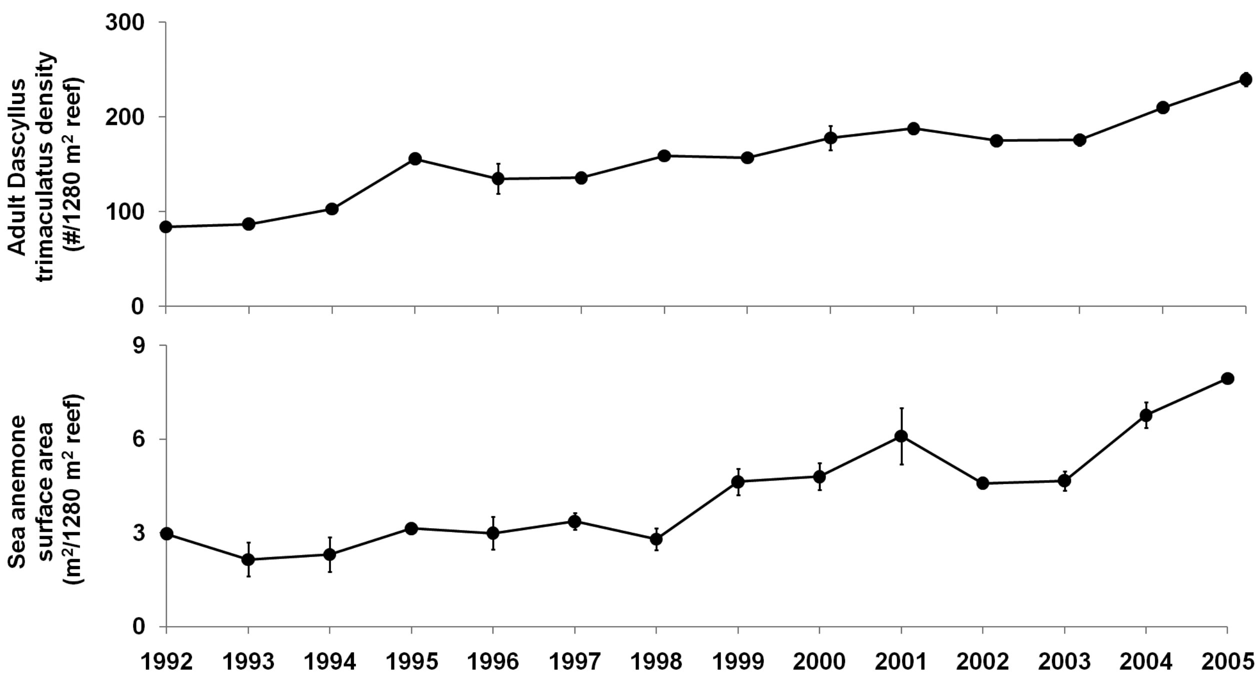

Figure A1-55. Adult abundances of a coral reef fish *(Dascyllus trimaculatus)* at Moorea Coral Reef (MCR) smoothly tripled over 2-3 population turnovers (top), closely tracking the pattern in abundance of the sea anemone *Heteractis magnifica* (bottom), which is the settlement and juvenile habitat for *D. trimaculatus* (R. Schmitt and S. Holbrook, unpublished data).

Niwot Ridge Research Area (NWT) [USFS, LTER]

http://culter.colorado.edu/NWT/

The Niwot Ridge (NWT) LTER program was established in 1980 to study ecological and hydrological processes in high-elevation areas in the Colorado Front Range of the Rocky Mountains. Research began at the site in the 1940s with the return of World War II veterans having extensive experience in cold-region logistics. Snowfall accounts for more than 80 percent of precipitation.

Subalpine forest can be found on the lower, gentler eastern slopes, whereas the higher, more rugged western portions of the ridge are nearly unvegetated (figure A1-56). Subalpine meadows and patches of krummholz sometimes are found in the abrupt transition between forest and tundra. The major research area is the Saddle, with its western half being a snow accumulation area (up to 10 m in some years) and its eastern half remaining free of snow for most of the winter. The interactions among wind, snow, and high topographic relief result in a mosaic of moisture availability to tundra plants with resulting effects on vegetation. The Saddle is characterized by different vegetation communities, including fellfield, dry meadow, moist meadow, shrub tundra, wet meadow, and snowbed.

Research focus. The goal of NWT research is to understand the causes of and ecosystem responses to climate change in high-elevation, seasonally snow-covered catchments. Changes in abundance and species composition of the native flora and fauna of these mountain ecosystems are potential bellwethers of global change. A suite of short- and long-term experiments are being conducted to better understand how alpine tundra and lakes respond to changes in climate and nutrient loading.

Figure A1-56. Niwot Ridge Research Area (NWT USFS/LTER) is located in the Rocky Mountains and ranges from subalpine forest to tundra. (Photo by Steven Schmidt.)

Long-term research example. The mountain glaciers of the world have been recognized as potentially sensitive indicators of environmental change. Because glaciers contain so little ice mass by comparison to the volume they accumulate from snowfall and lose to snow and ice-melt, glaciers of the Rockies may be particularly sensitive to environmental change. Estimates of the mass balance (accumulation minus melt of snow and ice over the year) on Arikaree Glacier have been made since 1981. Earlier studies from 1965 to 1974 extend these observations and make them the most comprehensive and continuous record for any of the small glaciers in the Front Range of the Rockies.

Since 1968, the annual net balance (NB) has been negative in 25 years and positive in 12 years, with 6 of those 12 years coming from the first decade (1968-1977) when the glacier experienced an accumulated gain of about 10 cm water equivalent (figure A1-57). From 1977 to 2000, most years show a negative NB with a total loss of about 13 cm water equivalent despite an increase in October -March precipitation. Further, the rate of loss since 1977 has accelerated by almost 2.5 cm/y. The drought years of 2001-2002 had winter precipitation only 65-70 percent of average, the lowest in 30 years of record. Such low volumes of snow accumulation, with relatively warm summers, resulted in a loss of 550 cm water equivalent. Since 2002, NB shows some recovery, but only back to the accelerating decline of the late 20th Century.

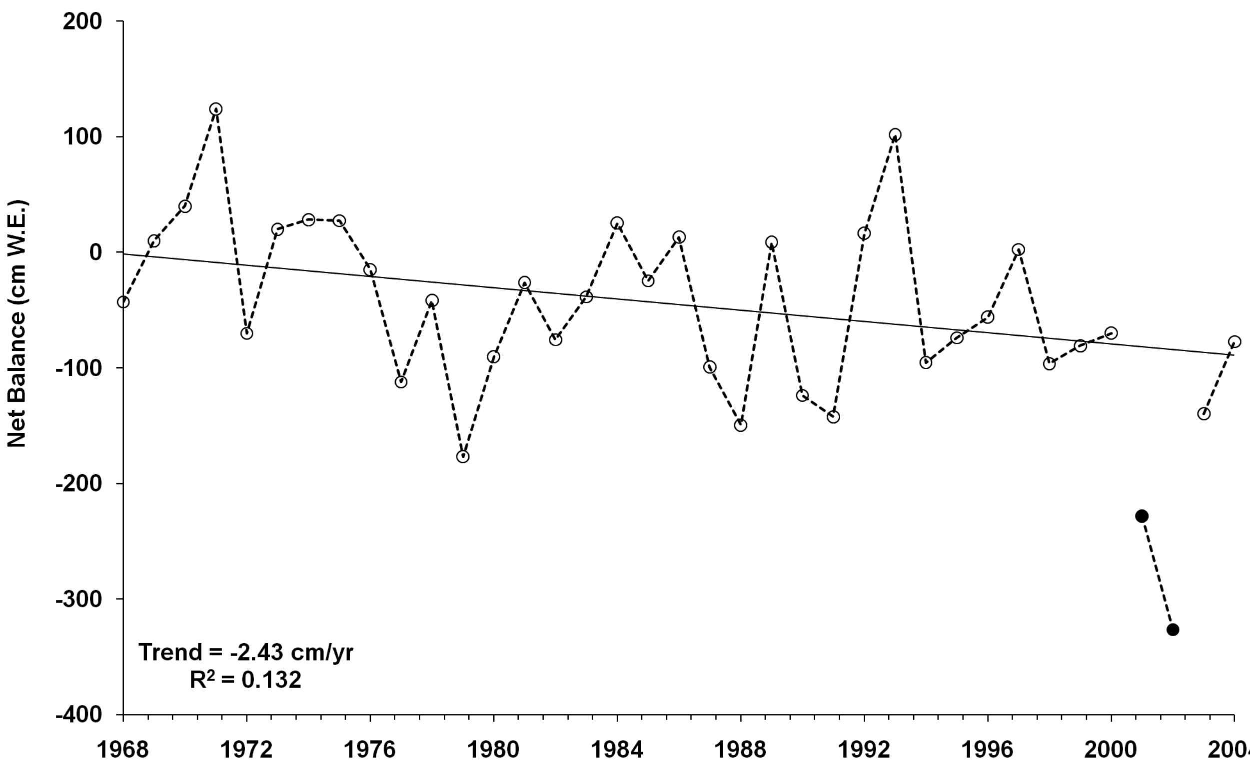

Figure A1-57. Arikaree Glacier at Niwot Ridge Research Area (NWT) has been losing mass (NB equals accumulation of mass minus melt of snow and ice) since 1965. The drought years of 2001-2002 are clearly evident in the loss of NB (T.N. Caine, in preparation).

North Temperate Lakes (NTL) [LTER]

http://lter.limnology.wisc.edu/

The North Temperate Lakes (NTL) LTER program was established in 1981 to understand the ecology of lakes in relation to relevant atmospheric, geochemical, landscape, and human processes. The NTL site comprises two geographically distinct regions: the Northern Highlands Lake District (NHLD) and the Yahara Lake District (YLD). These districts lie in formerly glaciated terrain of Wisconsin (figure A1-58). Lakes are the focal landforms of both regions, providing unique habitats, ecosystem services, and foci of human activity. The NHLD, one of the most lake-rich regions of the world, is largely forested and sparsely settled. Outdoor recreation centered on the 7,600 lakes of the region is a mainstay of the economy. The YLD is an agricultural, but urbanizing, landscape with scattered remnants of presettlement ecosystems. The diverse economy involves service industries, emerging technologies, some light industry, State government, and the State's flagship university. Ecological research began in the YLD in the 1880s and in the NHLD in the 1920s.

Research focus. The NTL's overarching research question is "How do biophysical setting, climate, and changing land use and cover interact to shape lake characteristics and dynamics over time (past, present, and future)?" Long-term research provides an opportunity to study natural and human disturbances through analysis of regional variability, historic data, and both episodic and chronic events. Whole-lake experiments are being used to understand how lakes respond to particular environmental changes (figure 4-3).

Long-term research example. Long-term observations of the phosphorus cycle and water clarity have revealed changes in water quality of Lake Mendota (Carpenter et al. 2007). Trends in dissolved reactive (mostly inorganic) phosphorus (DRP) in the surface waters reflect low sewage effluent inputs of phosphorus from upstream communities in the lake's watershed prior to 1945 (figure A1-59, top). Lake DRP concentrations increased dramatically due to an increase in effluent phosphorus inputs immediately after World War II. Following sewage effluent diversion from the lake in 1971, DRP concentrations remained high because of the increasing importance of agricultural and urban nonpoint source pollution. Variability in DRP concentrations since 1971 reflects periods of low and high inputs of phosphorus in runoff.

Figure A1-58. North Temperate Lakes Long Term Ecological Research (NTL LTER) consists of lakes in two lake districts in Wisconsin that differ in habitats, ecosystem services, and foci of human activity. (Photo from NTL photo gallery.)

Even though phosphorus concentrations stabilized at a higher level after 1950, water clarity (as measured by Secchi disk transparency) became highly variable (figure A1-59, bottom) as a result of changing levels of nutrients and herbivory (Lathrop et al. 1996). Intervals of high water clarity (deep Secchi depth) demonstrate the role of *Daphnia* (water fleas) in grazing the early spring phytoplankton in Lake Mendota. Throughout the early 1900s and from the late 1970s through the mid-1980s when planktivorous fish were abundant, predation on the larger-bodied *D. pulicaria* prevented their development early in spring. As a result, phytoplankton densities remained high with water clarity being relatively poor until around late May, when the smaller-bodied *D. galeata mendotae* with its higher temperature requirements for growth would clear the phytoplankton. In years when planktivorous fish were less abundant (1960s through the mid-1970s and since the late 1980s), *D. pulicaria* populations increased rapidly after iceout as reflected in the wide range of Secchi readings during the spring turnover period. Thus, the "clear water phase"—a common occurrence in eutrophic lakes—was initiated in Lake Mendota.

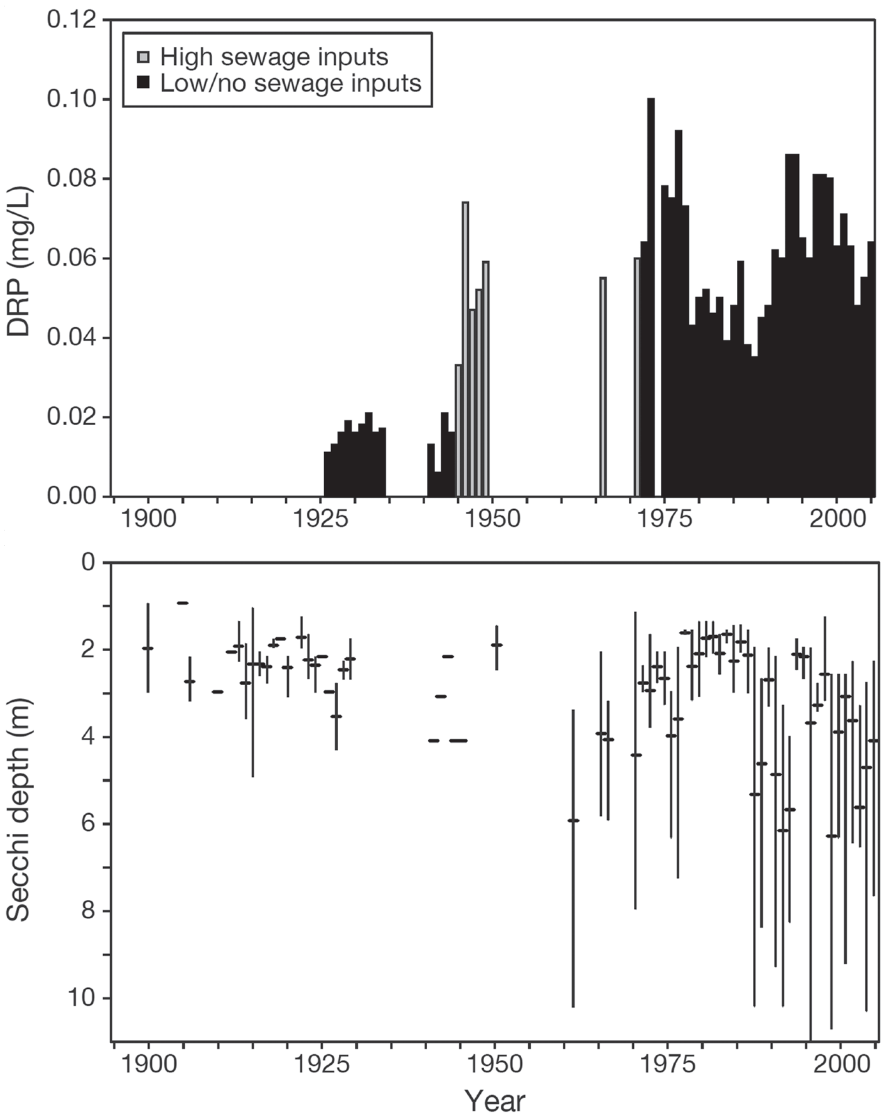

Figure A1-59. Long-term observations of the phosphorous cycle and water clarity in Lake Mendota (NTL) show both human influences and biotic interactions (Carpenter et al. 2007). Annual DRP averages were computed from the previous October through September if six or more months in a given year had concentration data. Spring turnover is defined as the period from ice out to May 10 prior to thermal stratification. For a given year, the short horizontal bar is the average of all spring turnover Secchi disk readings, and the thin vertical line is the range if more than one reading was taken. All readings were converted to 20-cm black-white disk readings. Data sources and conversion factors are described in Lathrop (1992). Reprinted with permission from the American Institute of Biological Sciences.

Palmer Station, Antarctica (PAL) [LTER]

http://pal.lternet.edu/

The Palmer, Antarctica (PAL), site joined the LTER in 1990 as the first marine pelagic site in the network. PAL is situated on the south coast of Anvers Island on the western Antarctic Peninsula. The site encompasses a larger region with several circumpolar pelagic habitats, including the continental shelf within the marginal ice zone covered seasonally by sea ice and the open ocean beyond the continental shelf break, as well as a nearshore zone influenced by glacial meltwater (Ducklow et al. 2007) (figure A1-60). Within the nearshore zone are small islands that have become deglaciated in the last few centuries.

Figure A1-60. The Palmer Station (PAL LTER) is a marine pelagic site off the western Antarctic Peninsula. Several species of penguins are studied in the nearshore zone. (Photo by Hugh Ducklow.)

Seabirds, including penguins, giant petrels, brown and south polar skuas, and other species, inhabit these islands along with mosses and two species of vascular plants. The nearshore waters abound in large marine mammals including seals (leopard, fur, crabeater, elephant, and Weddell), orcas, humpback whales, and minke whales. Palmer Station is occupied by humans year-round, but most scientific activity is concentrated in the Austral spring and summer.

Research focus. The primary goals of PAL are—

- to understand the dynamics of the Antarctic marine ecosystem as it is forced by interannual variations in sea ice,
- to document and predict ecosystem responses to rapid climate change, and
- to promote understanding of, and familiarity with, the Antarctic environment, climate change, and polar research.

There are two PAL fieldwork components: nearshore/seasonal and regional/annual. The nearshore work includes local oceanographic sampling in the water column (to depths of 50-100 m) and bird observations on nearby island breeding sites (figure 4-2), as well as experimental studies in the laboratory focusing on rate measurements of bacteria, phytoplankton, and krill metabolic and growth processes. Regional-scale sampling on the PAL Hydrographic Grid has been conducted every January since 1993. The extensive, whole-water-column survey data are aimed at documenting and analyzing the response of the pelagic ecosystem to climate variability and teleconnections, regional warming, and uncovering the mechanisms of the responses.

Long-term research example. Several sources of evidence show that warmer temperatures are influencing multiple facets of the Antarctic pelagic system (Vaughn et al. 2003, Ducklow et al. 2007). Long-term (1944-2005) temperatures at 65°12'S, 64°16'W show a mean winter (June through August) warming rate of 0.98 °C per decade (http://www.antarctica.ac.uk/met/data.html). At Palmer Station (64°46'S, 64°16'W), the mean winter warming rate is over 1 °C per decade, about five times the global average (figure A1-61).

Winter sea-ice duration (total annual days of sea-ice coverage) in the vicinity of Palmer Station is decreasing because autumn sea-ice advance is occurring later, while spring-summer sea-ice retreat is occurring earlier, shortening the winter sea-ice season by about 31 days per decade (Stammerjohn et al. 2008a). Smoothed standardized deviations (monthly anomalies divided by total standard deviations) of monthly sea-ice extent in the Palmer LTER study region is related to the Southern Oscillation Index (SOI) from 1979 to 2009 (Stammerjohn et al. 2008b). Negative SOI values indicate El Niño episodes in which positive sea-ice anomalies tend to occur (figure 3-1).

The prolonged period of La Niña (positive SOI) conditions (persistent and strong northwesterly winds) from 1998 to 2001 triggered the increased heat content delivered to the shelf water. The warming and changes in atmospheric circulation have resulted in increased transport of heat onto the continental shelf adjacent to the peninsula, as indicated by heat content of ocean water on the shelf, which has been shown to be linearly related to the ocean heat flux and shows a steady increase since 1993. This heat increase is sufficient to drive uniform warming of an approximately 300 m thick layer by 0.7°C.

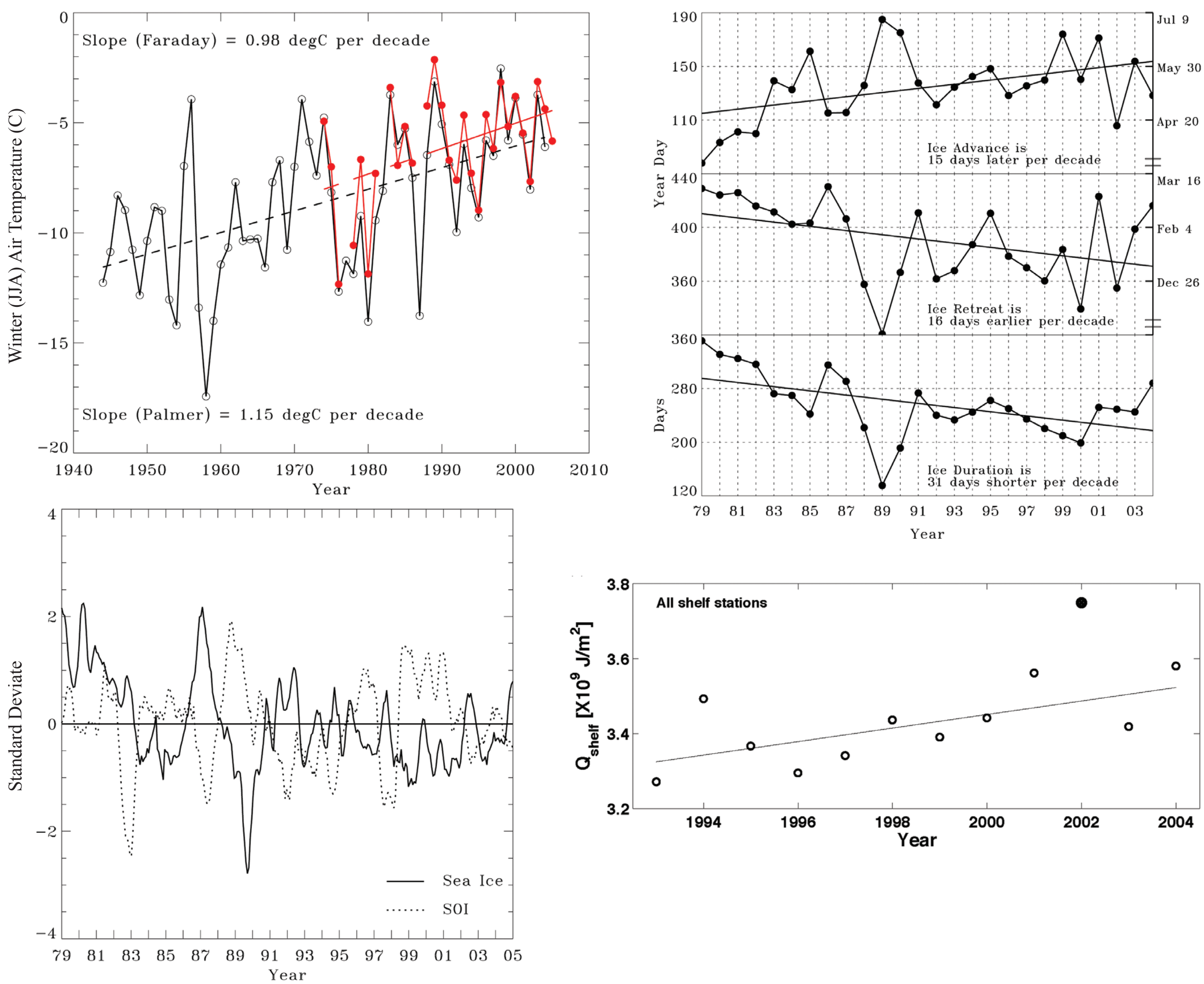

Figure A1-61. Top left: winter air temperature at two stations—black, Faraday/Vernadsky Stations (65°2'S, 64°6'W); red, Palmer Station (64°46'S, 64°16'W). Top right: autumn sea-ice advance, spring-summer sea-ice retreat, and winter sea-ice duration in the vicinity of Palmer and Faraday/Vernadsky Stations. Bottom left: smoothed standardized deviations (monthly anomalies divided by total standard deviations) of monthly sea ice extent in the Palmer Station Long Term Ecological Research (PAL LTER) study region and the Southern Oscillation Index (SOI). Bottom right: heat content of ocean water on shelf. (Figure derived from Stammerjohn et al. 2008a, 2008b.)

Plum Island Ecosystems (PIE) [LTER]

http://ecosystems.mbl.edu/PIE/

The Plum Island Ecosystems (PIE) LTER was established in 1998 with the goal of developing a predictive understanding of the long-term responses of watershed and estuarine ecosystems to changes in climate, land use, and sea level and to apply this knowledge to the management and development of policy that aims to protect the natural resources of the coastal zone. The coupled watersheds and estuary of Plum Island Sound are located near the Boston metropolitan region of northeastern Massachusetts. The Ipswich River (400 km^2) and Parker River (200 km^2) basins lie entirely within the Seaboard Lowland section of the New England physiographic province. The low relief of the basin is responsible for a large expanse of wetlands.

The estuary contains salt marsh dominated by smooth cordgrass *(Spartina alterniflora)* and marsh hay *(Spartina patens),* fresh marsh dominated by cattail *(Typha),* intertidal flats, and open-water tidal creeks and bays (figure A1-62). Species diversity is low, with half the number of fish species in areas south of Cape Cod. Plum Island Sound estuary supports productive commercial and recreational soft-shell clam and striped bass fisheries. Watershed land use composition in 2001 was approximately 46 percent forest, 34 percent urban/suburban, 10 percent agriculture, and 10 percent wetland and water.

Research focus. Research at PIE focuses on how inputs of organic matter and nutrients from land, ocean, and marshes interact with external drivers (climate, land use, river discharge, sea level) to determine the spatial patterns of estuarine productivity and trophic structure.

Figure A1-62. Plum Island Ecosystems (PIE LTER) consists of watershed and estuarine systems located near Boston in northeastern Massachusetts. (Photo from PIE photo gallery.)

Long-term research example. Nutrient-rich runoff from the terrestrial environment is one of the major factors leading to estuaries being among the most productive ecosystems on Earth. Nutrient inputs described on an areal basis, such as those used to describe fertilizer application rates on farms (measured, for example, as kg/ha of estuary), are often as high as the most intensively fertilized agricultural crops. However, excessive nutrient inputs can lead to estuarine eutrophication, a process that can lead to algal blooms, anoxia, and fish kills. Eutrophication is perhaps the most prevalent problem facing estuaries worldwide.

At PIE, nutrient inputs (loads of nitrogen and phosphorous) from the Ipswich River are substantially higher than from the Parker, primarily because the watershed is much larger (figure A1-63). Similar yields are likely due to efficient nutrient retention in the Ipswich River watershed (figure A1-63). This long-term dataset shows that nutrient load and yield from year to year have substantial variability that is not due to differences in nutrient inputs to the watershed, but rather is entirely attributed to variation in precipitation and water runoff. Nutrients accumulate during low-discharge years and then are flushed into the estuary during higher discharge years. This 4- to 5-fold difference in nutrient export between wet and dry years has a major influence on estuarine productivity.

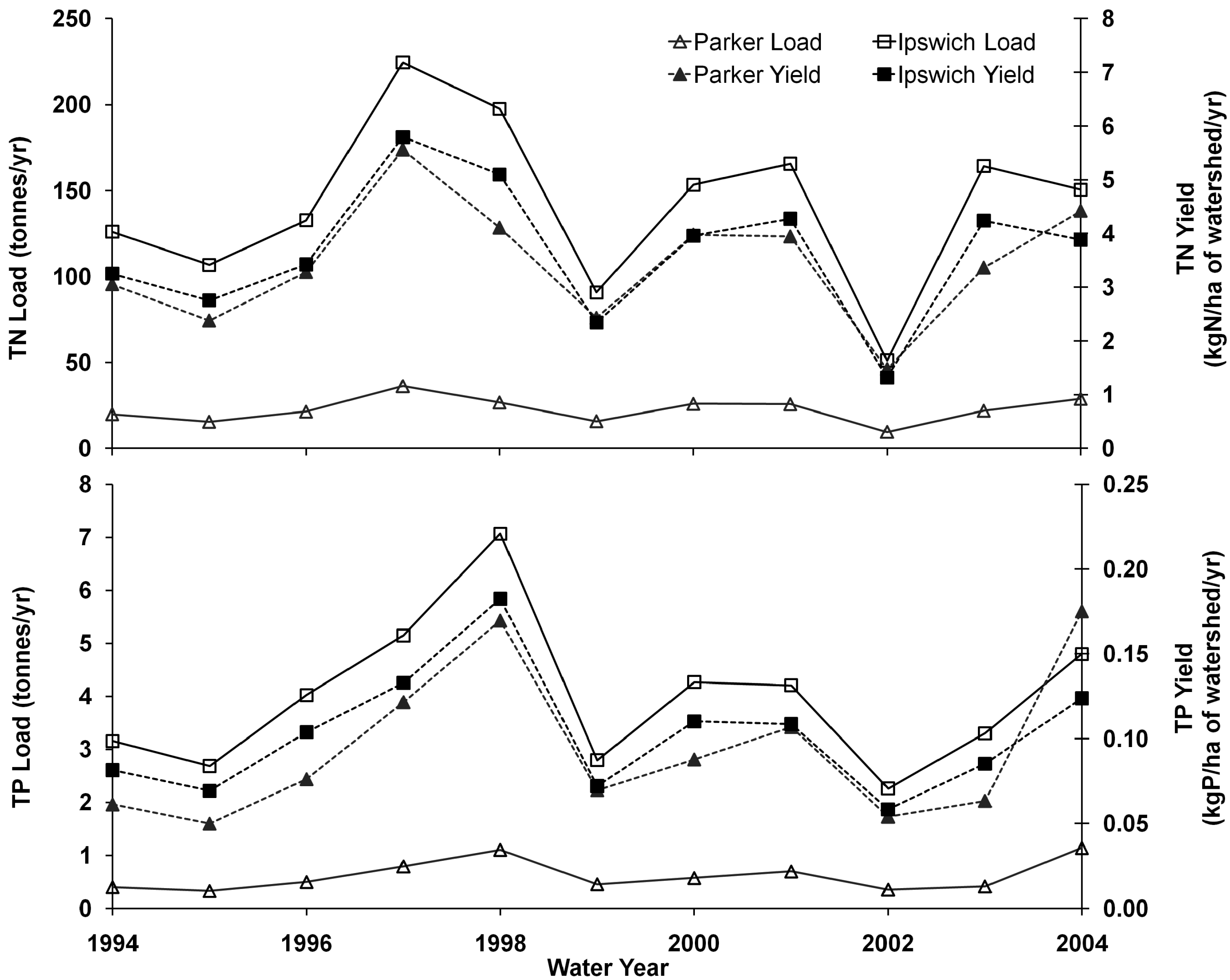

Figure A1-63. Substantial annual variability in nutrient load and yield in two rivers attributed to variations in precipitation and water runoff. Nutrient inputs from the Ipswich River are substantially higher than those from the Parker, primarily because the watershed is so much larger. Similar yields are likely due to efficient nutrient retention in the Ipswich River watershed. (See Williams et al. [2004] for methods.) Data are available at http://ecosystems.mbl.edu/PIE.

Priest River Experimental Forest (PRI) [USFS]

http://forest.moscowfsl.wsu.edu/ef/pref/

Established in 1911, the Priest River Experimental Forest (PRI) in northern Idaho contains approximately 2,758 ha (6,368 acres) of mountainous conifer forest, with small areas of talus and alpine grassland. Approximately 90 percent of the area is mountainous. Climate is transitional between a northern Pacific coastal type and a continental type. About two-thirds of PRI is covered in mixed conifer forest more than 100 years old, resulting from a fire in about 1860 (figure A1-64). The other third is nonstocked areas or is in young timber on harvest units and burn areas. Habitat is best described as complex because of the extremely rapid changes in aspect and in wetness/dryness of sites. Plant species diversity is high because of the number of different, intimately intermixed habitat types.

Research focus. Research focuses on the factors influencing forest fire, hydrology, silviculture, forest ecology, insects, and diseases of Rocky Mountain conifers. Projects have evaluated adaptability of native conifers to climate change, compared strategies for restoration of western white pine *(Pinus monticola),* compared mechanical site preparation as an alternative to prescribed fire, and evaluated the effects of wildfire and management activities on soil productivity and sediment transport. There have also been extensive studies of allometric functions, vertical trends in leaf mass per area, leaf turnover, and leaf area index. Recent work includes analyses of sap flow, nocturnal transpiration, isotopic mass balance of soil water, and hyperspectral remote sensing.

Figure A1-64. Priest River Experimental Forest (PRI USFS) is located in mountainous coniferous forest in northern Idaho. The office/laboratory building is in the center with the weather station at right. (Photo by Bob Denner.)

Reynolds Creek Experimental Watershed (RCE) [USDA-ARS]

http://ars.usda.gov/

The Reynolds Creek Experimental Watershed (RCE) was established nearly 50 years ago to address critical water issues on western rangelands. The RCE watershed (239 km^2) is located on rangeland in the north flank of the Owyhee Mountains about 80 km southwest of Boise, ID (figure A1-65). Primary land use is livestock grazing with some irrigated fields along the creek at the lower elevations and timber harvesting at higher elevations. Semi-arid sagebrush communities typical of the Great Basin are found at lower elevations, while aspen and Douglas-fir stands increase with elevation on deep soils.

Research focus. Research on the watershed has changed focus over the past 40 years, starting with monitoring and describing hydrologic processes and, over the decades, migrating toward development of computer-based tools to address critical water supply, water quality, and rangeland management problems. These tools are developed in an environment of intense monitoring and field experimentation. Currently, there are 104 data collection sites in the RCE measuring environmental parameters such as streamflow, snow depth, precipitation, soil water, and temperature. Specific research projects include the following:

- Studies of pre- and post-fire hydrology to evaluate the hydrologic impacts of juniper invasion and juniper removal and to evaluate prescribed-fire impacts on other vegetation, soil, and animal resources. Results show that erosion is reduced after juniper removal and recovery of grasses.
- Research on snow accumulation and snowmelt dynamics in mountainous terrain, working with USDA Natural Resources Conservation Service on use of snowmelt modeling tools to improve streamflow forecasting.
- Evaluation of telemetry tracking collars to determine how prescribed fire treatments for juniper and brush control affect cattle distribution and activity patterns.

Figure A1-65. Reynolds Creek Experimental Watershed (RCE USFS) is located in southwestern Idaho and includes Great Basin rangeland at low elevations with aspen and Douglas fir communities at higher elevations. Streamflow is measured using a drop-box weir. (Photo from RCE photo gallery.)

Santa Barbara Coastal (SBC) [LTER]

http://sbc.lternet.edu/

The Santa Barbara Coastal (SBC) LTER was established as an LTER site in 2000 to understand the linkages among ecosystems at the land-ocean margin. The principal study site is the semi-arid Santa Barbara coastal region, which includes steep watersheds, small estuaries, sandy beaches, and the neritic and pelagic waters of the Santa Barbara Channel and the habitats encompassed within it (figure A1-66).

One of the more notable habitats is shallow rocky reefs dominated by giant kelp *(Macrocystis pyrifera)* forests. The rapid growth and high turnover of giant kelp result in very high rates of primary production and make these underwater forests one of the most productive systems on Earth. The characteristic three-dimensional structure of giant kelp, coupled with its extremely high productivity, enables kelp forests to provide food and habitat for a diversity of algae, invertebrates, fishes, birds, and marine mammals, many of which are ecologically and economically important.

Research focus. The focus of SBC research is developing a predictive understanding of the structural and functional responses of giant kelp forest ecosystems to environmental forcing from land and sea. The amount of nutrients and organic matter delivered to these forests varies in response to short- and long-term changes in drivers such as climate, ocean conditions, and land use. Variation in the supply of these commodities interacts with physical disturbance to influence the abundance and species composition of the forest inhabitants and the ecological services that they provide. Although there is increasing concern about the effects of human activities on coastal watersheds and near-shore marine environments, there have been few long-term studies of the linkages among the coastal ocean, shallow near-shore reef, and terrestrial habitats. SBC studies these effects of oceanic and coastal watersheds on kelp forests in the Santa Barbara Channel (figures 4-5, 4-6, 9-15).

Figure A1-66. Santa Barbara Coastal (SBC LTER) in a SPOT image of the Santa Barbara coast showing kelp forests in shallow water. © CNES 2006, distributed by Terra Image USA.

Long-term research example. The giant kelp is the world's largest alga; it forms dense forests in many regions of the world. Giant kelp plays a very important ecological role in providing food and shelter to a diverse assemblage of animals, many of which are fished. Giant kelp itself is harvested for use in a wide variety of food and industrial products. A marine reserve system was established in 2002 in the waters surrounding the California Channel Islands at the SBC site to protect kelp forests and other valued marine habitats and species from commercial and recreational harvesting.

The biomass of kelp showed a 20-fold increase in the reserve off Santa Rosa Island shortly after it was established (figure A1-67, top), suggesting that restrictions on harvesting kelp and the predators of animals that eat kelp have an immediate effect on kelp populations. However, a longer term view of the kelp population reveals that the increase in biomass following the establishment of the reserve was quite small, compared with what has occurred at this site over the last 50 years (figure A1-67, bottom). This example illustrates the need for long-term data when evaluating the effectiveness of conservation efforts designed to enhance species such as giant kelp whose abundance fluctuates greatly from year to year.

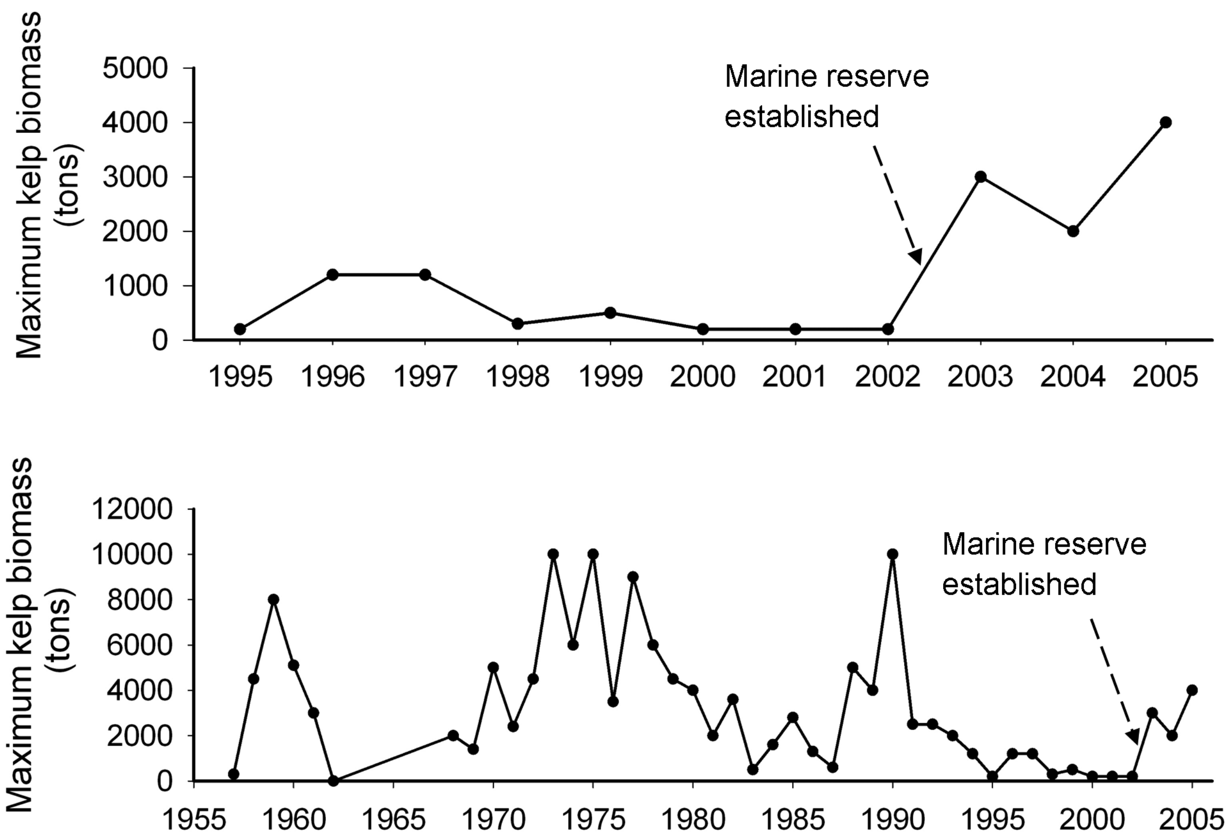

Figure A1-67. Kelp biomass increased following the establishment of a marine reserve (top), but this increase is within the natural variability in kelp biomass over the past 50 years at the Santa Barbara Coastal (SBC) (bottom). (Data available at http://sbc.lternet.edu/data/index.html.)

Santa Rita Experimental Range (SRE) [University of Arizona]

http://cals.arizona.edu/SRER/

The Santa Rita Experimental Range (SRE) was established in 1902 as the first in a series of U.S. Department of Agriculture facilities dedicated to understanding the ecology of arid environments and to developing methods for sustainable livestock grazing. Located on the western flank of the Santa Rita Mountains (45 km south of Tucson, AZ), the 21,500-ha SRE includes variation in elevation (900-1,450 m), precipitation (28-45 cm/y, about half occurring from July to September), and mean annual temperature (16-19 ºC). Thirty-two soil series are delineated as 24 mapping units. Plant communities include Sonoran desertscrub, semidesert grassland, and oak woodland with major transitions through time (figure A1-68). The flora includes 468 species, with greatest representation from the Poaceae (81 species), Asteraceae (72 species), and Fabaceae (61 species).

Research Focus. The SRE facilitates research activities in the tradition of a natural history field station. Early accomplishments included the first systematic estimates in the United States of livestock carrying capacity based on ANPP and the first use of repeat photography to record changes in vegetation. The program grew to include investigations in small mammal biology, soil moisture dynamics, and the effects of fire, as well as research in grazing management and restoration of arid landscapes degraded by drought and overgrazing. Current research includes ecosystem biogeochemistry related to carbon sequestration, co-evolution of plants and pollinators, and adaptive management of livestock grazing in a variable environment.

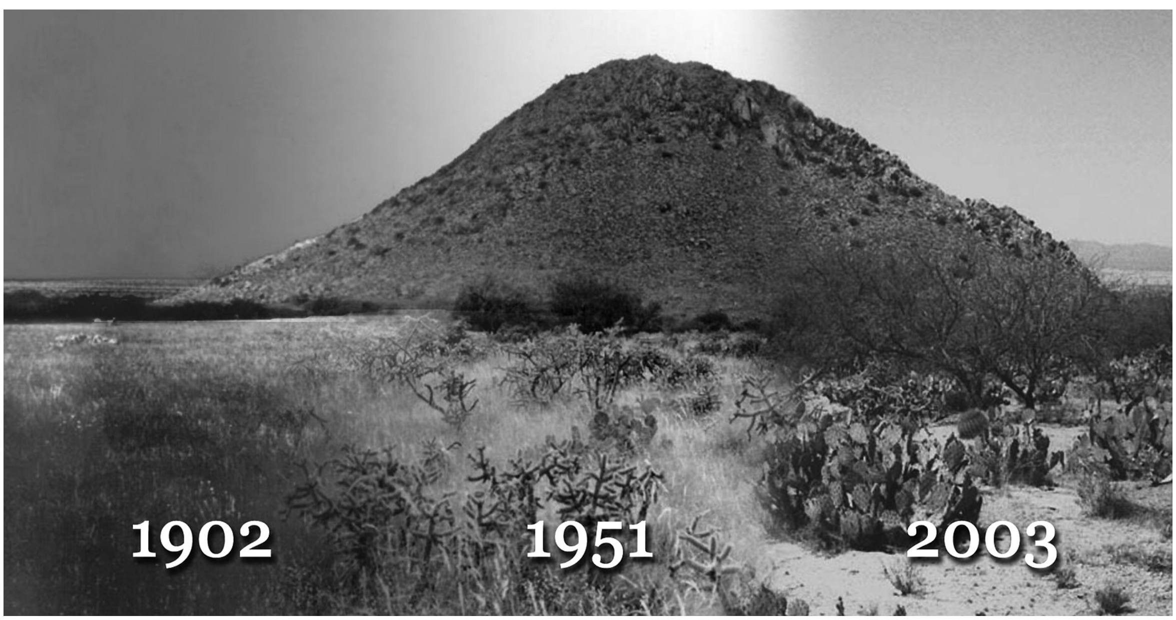

Figure A1-68. Santa Rita Experimental Range (SRE UA) near Tucson, AZ, is representative of Sonoran desert scrub vegetation. Repeat photography (available from http://ag.arizona.edu/SRER/photos.html) is used to record changes in vegetation. (Photo montage by Robert Wu.)

Santee Experimental Forest (SAN) [USFS]

http://www.srs.fs.usda.gov/charleston/

The Santee Experimental Forest (SAN) was established in 1937 in the forested landscape of the southeastern Atlantic Coastal Plain. Located in Berkley County, SC, the SAN encompasses some of the earliest colonized lands in the United States. Much of the uplands was cleared for agriculture, and the bottomlands were used for rice and indigo cultivation (figure A1-69). The SAN encompasses 2,469 ha, containing all the major forest types in the lower coastal plain occurring on three general land types: sandy ridges, broad flats, and floodplains. The dominant forest cover is mixed pine-hardwood and loblolly pine *(Pinus taeda)* stands with bottomland hardwoods occupying the riparian zones. Soils developed in marine sediments and fluvial deposits at elevations between 4 and 13 m above sea level. Climate is warm-temperate, and about 40 percent of rainfall occurs from June to August. Snowfall and ice storms are extremely rare. Tropical storms are a common hazard between August and October.

Despite the long land use history and repeat disturbance by hurricanes, the composition and productivity of the forest suggests dynamic and resilient ecosystems. Approximately 70 percent of the SAN is included in the Habitat Management Area for the red cockaded woodpecker, a federally listed endangered species. While much of the southeastern coastal landscape is being fragmented and developed, the SAN serves as an important reference for understanding ecosystem processes in a suburbanizing landscape.

Figure A1-69. Santee Experimental Forest (SAN USFS) in South Carolina was established in the forested landscape of the southeast Atlantic coastal plain. (Photo from SAN photo gallery.)

Research focus. Research traditionally focused on silviculture and prescribed fire effects. Studies have encompassed many aspects of silviculture, including harvesting, regeneration, thinning, and fertilization. Studies have also been conducted to assess the effects of prescribed fire on forest growth and composition and soil properties. With the establishment of four gauged watersheds in the 1960s, the fire and silviculture research could be conducted at a larger spatial scale. However, long-term silvicultural studies ended as a result of Hurricane Hugo. Ongoing research involves forest succession following hurricane disturbance, forest hydrology, carbon and nutrient cycling, and wildlife. The paired first-order watersheds are being used to assess effects of fuel management treatments in stands characteristic of post-hurricane regeneration. The SAN also serves as a platform for evaluating biogeochemical and hydrologic models.

Long-term research example. Measurements of streamflow (outflow) from a weir show similar trends to patterns in rainfall (figure A1-70). The data gap in 1982-1990 is partly attributed to Hurricane Hugo in 1989.

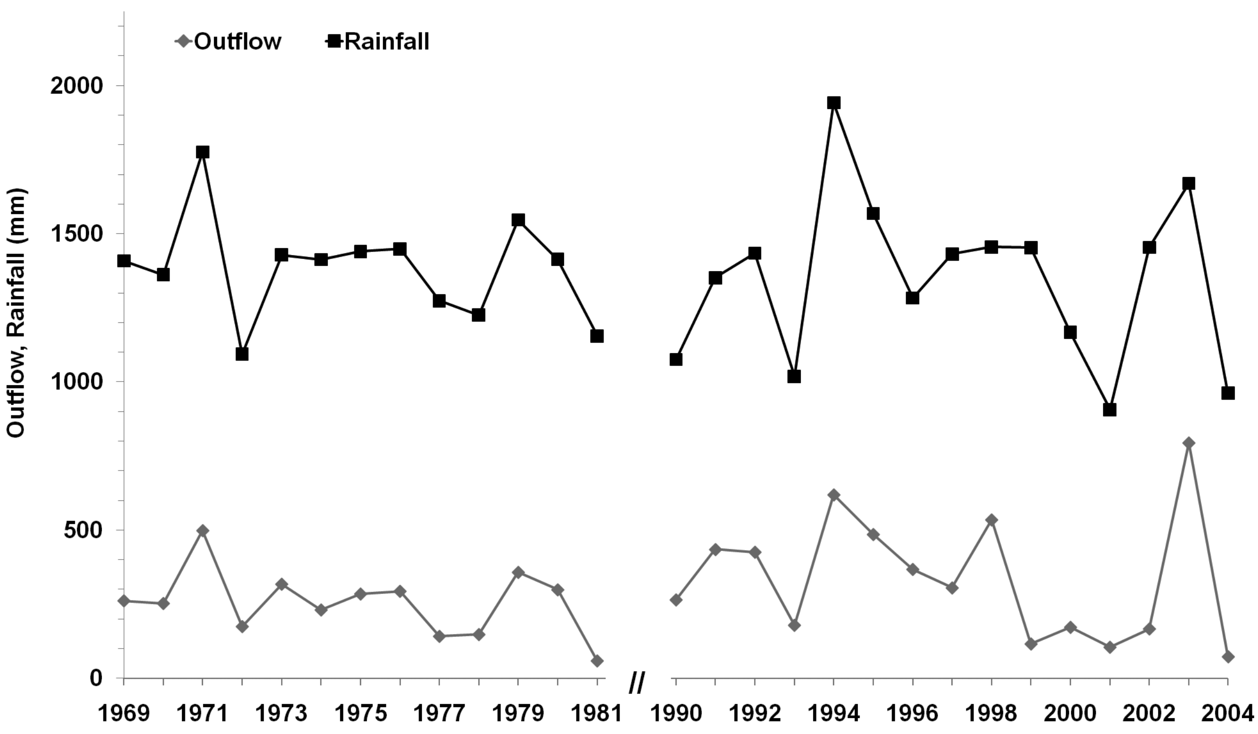

Figure A1-70. Streamflow measured as outflow from a weir follows a similar pattern as rainfall at the SAN. Data from http://www.fsl.orst.edu/hydrodb/.

Sevilleta (SEV) [LTER]

http://sev.lternet.edu/

The Sevilleta (SEV) was established as an LTER site in 1988 on the Sevilleta National Wildlife Refuge (U.S. Department of the Interior, Fish & Wildlife Service) to assess the effects of climate change, nitrogen deposition, and severe and prolonged wet and dry years on community and ecosystem processes at a biome transition zone. The site is located 80 km south of Albuquerque, NM. The climate is characterized by an abundance of sunshine, a wide range between day and night temperatures, and low relative humidity. Sixty percent of annual rainfall occurs during the summer monsoon from July through September. Extreme droughts occur on about a 50-year cycle. Cattle grazing has been excluded from the SEV since 1973.

Dominant plant species representing different biomes include *Bouteloua eropioda* (black grama) and *Larrea tridentata* (creosote bush) from the Chihuahuan Desert (figure A1-71), *Juniperus monosperma* (one-seed juniper) and *Pinus edulis* (piñon pine) from higher elevations, and *Bouteloua gracilis* (blue grama) from the shortgrass steppe in the Great Plains.

Figure A1-71. The Sevilleta Long Term Ecological Research (SEV LTER) site encompasses the transition between four major biomes, including the transition zone between Chihuahuan Desert shrubland (foreground) and grassland (background). (Photo by Robert R. Parmenter.)

Research focus. Studies at the SEV are linked by an overarching theme: how abiotic drivers and constraints affect dynamics and stability in aridland populations, communities, and ecosystems (Collins et al. 2008). Studies are conducted on soil structure and development, soil carbon and nitrogen pools and fluxes, vegetation patch structure and species interactions, and the role of consumers among habitats and especially across the grassland-to-shrubland transition zone.

Long-term research example. Species richness and cover are variable for functional groups at two transitional locations dominated by species from different biomes (figure A1-72). At both sites—Deep Well (Chihuahuan Desert-Shortgrass steppe site) and Five Points (Chihuahuan Desert shrubland-Chihuahuan Desert grassland site)—cover of grasses, richness of forbs, and total cover and richness are increasing through time. These changes may reflect the cessation of grazing in the 1970s, which favors grasses combined with increased fire frequency, which limits shrubs and increases forb species richness.

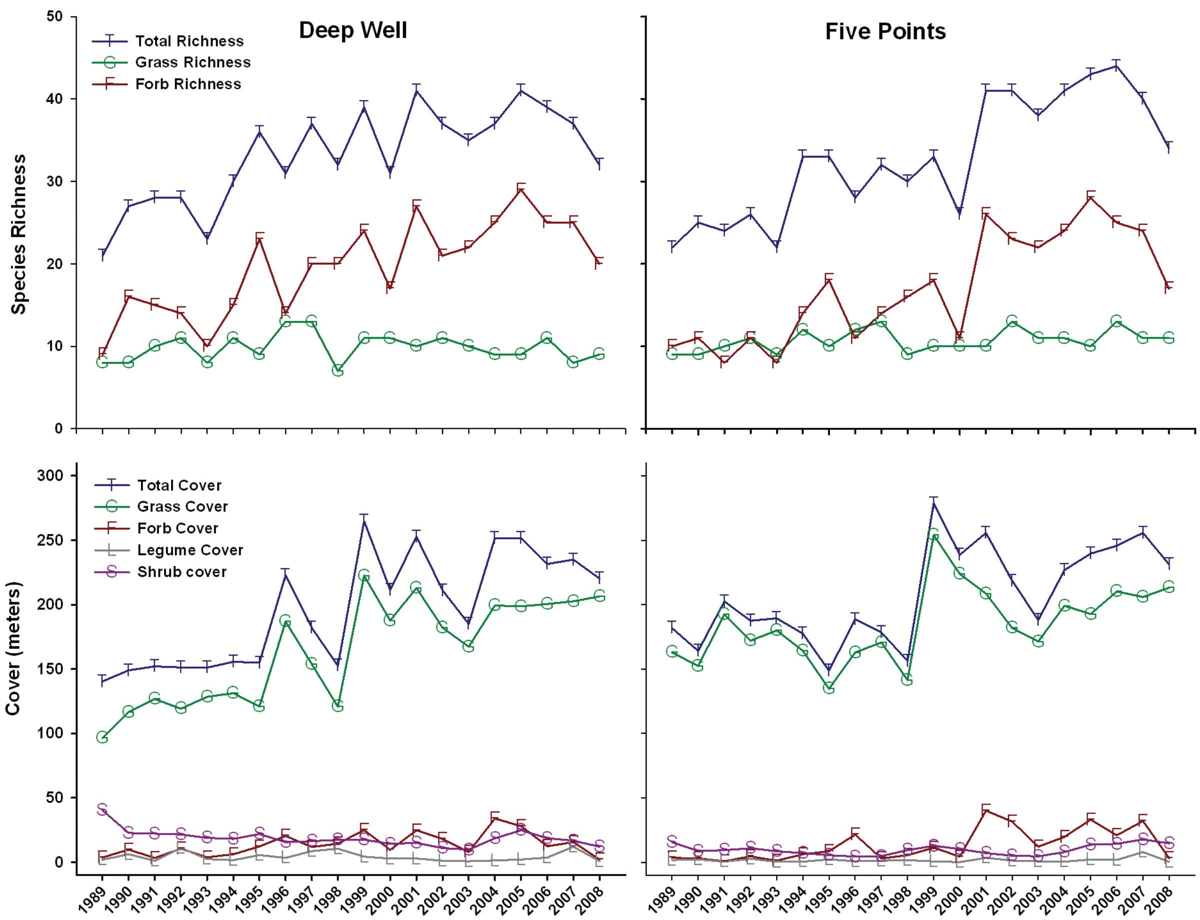

Figure A1-72. Species richness and cover vary by functional group at two locations in Sevilleta (SEV). Increases in grass cover and shrub richness result in an increase in total cover and richness at both locations (Collins and Xia, unpublished data).

Shortgrass Steppe (SGS) [USDA-ARS, LTER]

http://www.sgslter.colostate.edu/

The Shortgrass Steppe (SGS) was established as an LTER site in 1982 to study how climate, natural disturbance, physiography, and human activities influence communities of plants and animals; how they drive cycling and storage of carbon, nitrogen, and methane; and ultimately how the shortgrass steppe ecosystem responds. Studies are conducted on the USDA-ARS Central Plains Experimental Range and the Pawnee National Grasslands of the USDA Forest Service.

Topography is gently rolling with broad valleys and ephemeral streams. Soils are principally derived from alluvium and wind-reworked sediments eroded from local sedimentary rock formations and the nearby Rocky Mountains. Climate is typical of mid-continental semiarid temperate zones, but is somewhat drier because of a strong rain shadow effect of the Rocky Mountains. Approximately 70 percent of the precipitation falls during the April-September growing season. The ecosystem is dominated by short grasses (64 percent), succulents (21 percent), and dwarf shrubs (8 percent) (figure A1-73). Blue grama *(Bouteloua gracilis)* predominates and contributes 60 to 80 percent of plant cover, biomass, and net primary productivity. The disturbance regime includes a number of types of disturbances (figures 9-7 and 9-16).

Figure A1-73. Shortgrass steppe vegetation is dominated by warm season grasses at the Shortgrass Steppe (SGS) USDA-ARS/LTER site. (Photo by Amy A. Yackel Adams.)

Research focus. The mission of the SGS is to investigate the inter-relationships among climate, natural disturbance, physiography, and human use on ecosystem structure and function (figure 5-2). Located on the western edge of the central Great Plains, the shortgrass steppe is characteristic of North American grasslands with its long history of grazing by large herbivores and periodic drought. Over time, intense selection by grazing and drought has created an ecosystem that is well adapted to both, with low-standing vegetation and below-ground concentration of biological activity and organic matter. Currently, grazing by domestic livestock is the primary use of native grassland, which occupies about 60 percent of the shortgrass steppe.

Long-term research example. By 1920, much of the SGS area was settled by homesteaders who planted crops, such as corn, that are typical of wetter areas. During periods of drought, repeated crop failures led to widespread abandonment of fields; land purchases by the Federal Government resulted in the two parts of the SGS site.

A number of studies were conducted in the mid-1900s to evaluate recovery patterns on old fields. These studies showed four stages of succession dominated by different species groups (figure A1-74). The final, "climax," stage was predicted to occur 25 to more than 50 years after abandonment and represents a traditional Clementsian model. However, an alternative model was proposed in the 1970s in which the subdominant grass stage lasts indefinitely as an alternative state of the system (figure A1-74). More recent results from the SGS using 13 fields with similar soils and length of time following abandonment (53 years) found high variability in cover of shortgrasses (12-88 percent; figure A1-74) (Coffin et al. 1996). Only two fields (11 and 12) had high shortgrass cover similar to predictions from the Clementsian model, and only two (4 and 8) had low shortgrass cover similar to the alternative states model. Most fields had intermediate values that did not fit either model. High variability in recovery of shortgrasses after large disturbances led to an alternative view of the role of disturbance, one that focuses on interactions between individual plants and their environment, including disturbance characteristics, in determining recovery rates and patterns (Peters et al. 2008, 2011).

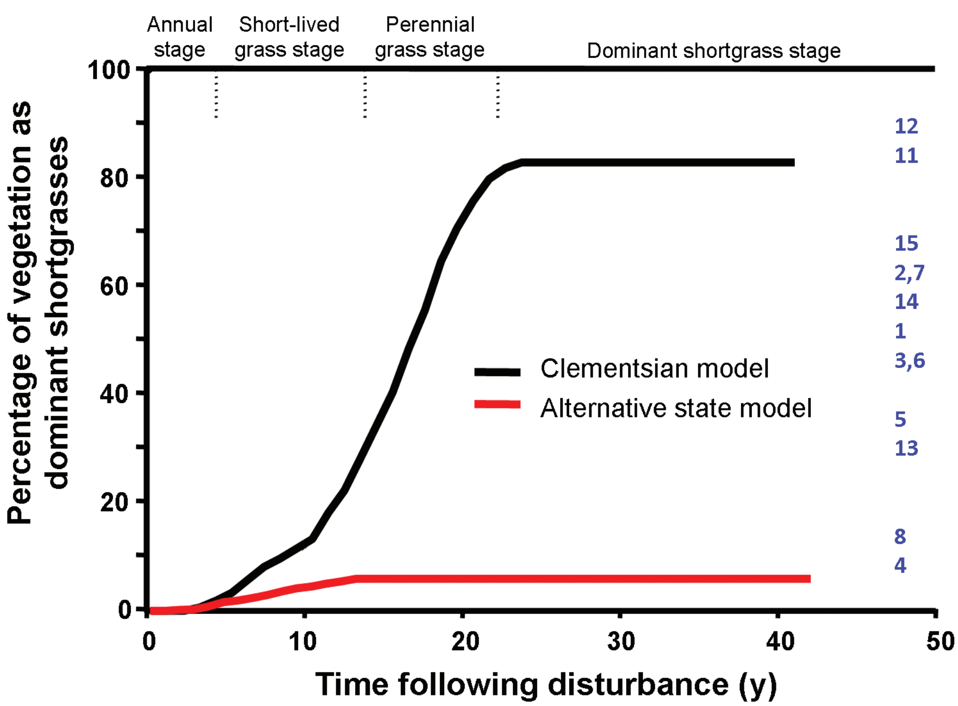

Figure A1-74. Comparison of predictions of shortgrass cover through time for two old-field models of succession (Clementsian model in black, alternative state model in red) and actual shortgrass cover found on 13 fields sampled 53 years following abandonment at the Shortgrass Steppe (SGS) site (blue numbers). (Redrawn from Coffin et al. 1996.)

Southern Plains Range Research Station (SPR) [USDA-ARS]

http://www.ars.usda.gov/

The Southern Plains Range Research Station (SPR) was established in 1913 at Woodward, OK. The predominant native vegetation is southern mixed-grass prairie dominated by sand sagebrush *(Artemisia filifolia)*. Perennial grasses (short, mid, and tall) are the major complement to sagebrush. Blue grama *(Bouteloua gracilis)* and sand dropseed *(Sporobolus cryptandrus)* provide much of the basal cover and forage production.

Precipitation is unimodal with a peak in May. Moderate to severe droughts lasting several years is a feature of the climate. Temperatures range from a high of 46 ^{o}C to a low of -28 ^{o}C with an average daily high temperature of 21 ^{o}C and an average low of 8 ^{o}C. The frost-free growing season varies from 155 days to 243 days and averages 201 days.

Deep sandy soils (loamy sands and sands) on hilly landscapes without well-defined surface drainages are common. Faster infiltration and less water loss to evaporation make sandy soils more efficient than finer textured soils in supplying water to perennial plants.

The wind erosion potential of soils is high on disturbed or cultivated areas. Most soils prone to wind erosion have largely been reseeded to native and introduced warm-season grasses.

Research focus. The mission of the SPR is to develop and transfer innovative production practices based on fundamental ecological principles and to breed, select, and release improved plant germplasm to enhance sustainable forage and livestock production. Major range management practices include controlling stocking rate and season of use, using complementary forages, and controlling sand sagebrush, which is believed to increase in density as grazing pressure increases. However, canopy cover by sand sagebrush showed no major trend over 40 years under moderate grazing or in enclosures protected from livestock.

Tallahatchie Experimental Forest (TAL) [USFS]

http://www.srs.fs.usda.gov/

The 1,416-ha Tallahatchie Experimental Forest (TAL), located in the Holly Springs National Forest near Oxford, MS, was established in 1950 to study relationships between mixed pine and hardwood forests, flooding, and soil erosion. The TAL was established following the severe erosion and flooding that came after extensive forest clearing in the upper Coastal Plain during the early 20th century. The region's hilly upland soils exhibited some of the greatest erosion rates recorded in North America.

The TAL is typical of the upper Coastal Plain of the Mid South. Much of the northern portion lies within the bottomland forest adjacent to the Little Tallahatchie River. The central and southern portion is hilly terrain drained by a number of small forested streams. Slopes range from 15 to 30 percent, and relief within these small headwater basins varies between 30 to 40 m. Soils consist of predominantly Coastal Plain sandy loams and smaller amounts of silt loams. Forest cover is 55- to 65-year-old mixed shortleaf pine and hardwood (white and red oaks and hickories), which have been only minimally disturbed since establishment.

Climate is hot, humid summers and fairly mild winters with occasional ice storms and small amounts of snow. Annual precipitation averages over 1,300 mm and is evenly distributed through the year. The growing season lasts about 218 days. Brief, high-intensity convective storms can occur throughout the year but are more common in spring and summer. Most winter precipitation results from less intense, cyclonic weather fronts. Soil temperatures rarely fall below freezing.

Research focus. Past research focused on how different vegetation types (for example, old field, poorly stocked forests, overstocked forests) and silvicultural methods affect surface runoff and sediment yields. This knowledge contributed to the success of the Yazoo-Little Tallahatchie Project, a Federal reforestation and soil stabilization program from 1949 to 1985 throughout the upper Coastal Plain of northern Mississippi.

The TAL provides a unique variety of mixed pine-hardwood forest conditions within which management disturbances have been very limited, natural wildfire has been suppressed, and prescribed burning has been carefully controlled. Recent investigations have studied—

- how plant and bird communities respond to varying fire regimes,
- how tree species composition varies with fire frequency,
- how avian community structure and nest success are affected by prescribed burning, and
- how cool-season prescribed fire affects herbaceous, understory, and overstory vegetation.

Virginia Coast Reserve (VCR) [LTER]

http://www.vcrlter.virginia.edu/

The Virginia Coast Reserve (VCR) LTER program was established in 1987 to examine how long-term changes in climate (storms, temperature), sea level, and land use affect the dynamics and biotic structure of coastal barrier systems and the services they provide. The VCR extends over 110 km on the Eastern Shore of Virginia from the Maryland border to the mouth of the Chesapeake Bay and is characteristic of coastal barrier ecosystems along much of the Atlantic and Gulf Coasts (figure A1-75).

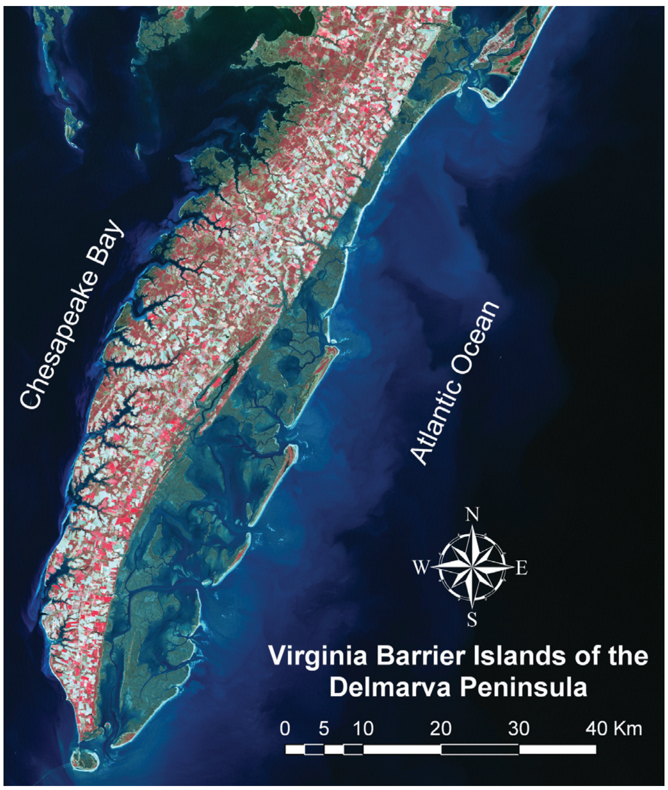

Figure A1-75. The Virginia Coast Reserve (VCR LTER) barrier island/lagoon system extends 110 km along the Atlantic shore of the Delmarva Peninsula. Sandy and dynamic barrier islands are backed by salt marshes and shallow lagoons and separated from one another by deep inlets. (Image from NASA Enhanced Thematic Mapper, 2001.)

The reserve comprises an extremely dynamic landscape that includes an assemblage of 14 barrier islands, shallow lagoons with extensive mudflats, tidal marshes, and mainland watersheds. It is one of the few remaining undisturbed coastal barrier landscapes in the Nation. The shallow seaward slope of the landscape (less than 0.1 percent) makes this a particularly sensitive location for studying responses of intertidal marshes to sea-level rise. The islands of the VCR are among the most dynamic in the United States; lateral accretion and erosion rates are as high as 13 m/y, highest along the Mid Atlantic Seaboard (figure 9-5).

At the turn of the last century, the barrier island and lagoon system supported one of the most prosperous farming- and fishing-based communities in the country. Towns on the islands were abandoned after the Great Storm of 1933, and the scallop fishery collapsed with the loss of seagrass around the same time. The VCR LTER program is now working with collaborators to restore seagrass to the region.

Research focus. Current research focuses on whether changing land use will affect water quality in VCR coastal bays and the recolonization of the seagrass as the foundation species, whether marshes can keep pace with one of the highest recorded rates of sea-level rise on the Atlantic Coast, and whether spatial variations in species and community distribution patterns on the islands can be used to predict areas vulnerable to change. Research is organized around three synthetic questions:

- How do long-term drivers of change (climate, rising sea level, land-use change) and short-term disturbance events interact to alter ecosystem dynamics and state change, and how is their effect modified by internal processes and feedbacks at the local scale?
- How do fluxes of organisms and materials across the landscape influence ecosystem dynamics and state change?
- In the future, what will be the structure of the landscape and what processes will drive ecological state change?

Walker Branch Watershed (WBW) [U.S. Department of Energy]

http://walkerbranch.ornl.gov

Walker Branch Watershed (WBW) was established in 1967 to quantify land-water interactions in a forested landscape. The WBW is located about 40 km west of Knoxville in the Ridge and Valley Geophysical Province of eastern Tennessee. WBW is a 97.5-ha forested watershed that resides within the U.S. Department of Energy Oak Ridge National Environmental Research Park, which encompasses over 8,000 ha of protected and mostly forested land devoted to research and education in the environmental sciences (figure A1-76).

Figure A1-76. Walker Branch Watershed (WBW DOE) near Knoxville, TN, is located in eastern deciduous forest. Stream studies are a prominent part of the site and research. (Photo by Brian Roberts.)

The climate is typical of the humid southern Appalachian region with little seasonality in rainfall. The vegetation is primarily chestnut oak *(Quercus prinus),* white oak *(Quercus alba),* tulip poplar *(Liriodendron tulipfera),* and red maple *(Acer rubrum),* which together account for about 70 percent of the total basal area. Hickory (*Carya* spp.) and shortleaf pine *(Pinus echinata)* were historically important minor components, but insect infestations have greatly reduced their abundance. The forest is of mixed age; the watershed was primarily in subsistence agriculture and open woodland prior to acquisition by the U.S. Government in 1942.

The soils are primarily Ultisols with small areas of Inceptisols in alluvial areas adjacent to streams. Soils are generally well drained, with high infiltration capacity, and are acidic (pH 4.2-4.6) and low in exchangeable bases, nitrogen, and phosphorus (Johnson and Van Hook 1989).

Research focus. The WBW project has three primary objectives:

- Provide base-line values for unpolluted natural waters within an urbanizing landscape.
- Contribute to our knowledge of cycling and loss of chemical elements in forest ecosystems.
- Enable development of models for predicting the effects of human activities on the landscape (especially climate change, atmospheric deposition, and air quality).

Long-term measurements include atmospheric inputs and stream outputs of water and chemicals, soil chemistry surveys, and forest vegetation inventories. Stream studies continue to be a prominent component of WBW research, particularly the role of stream processes in controlling stream nutrient concentrations and catchment outputs. Several studies have investigated nitrogen cycling and retention using tracer ^{15}N addition experiments (for example, the Lotic Intersite Nitrogen Experiment—LINX; see chapter 10). Whole-stream rates of metabolism (gross primary production, ecosystem respiration) have been measured continuously since 2004.

Long-term research example. The climate at WBW has been warming over the past 40 years (figure A1-77, top). Warming is higher during winter, with average air temperatures for January-March increasing at a rate of 0.72 ˚C/y, about twice the rate of annual temperatures. Annual precipitation and runoff are highly variable with no significant trends. There are no significant trends in wet nitrogen deposition and dissolved inorganic nitrogen (DIN) output, and nitrogen retention in the catchment is very high (DIN outputs are about 5 percent of wet nitrogen inputs).

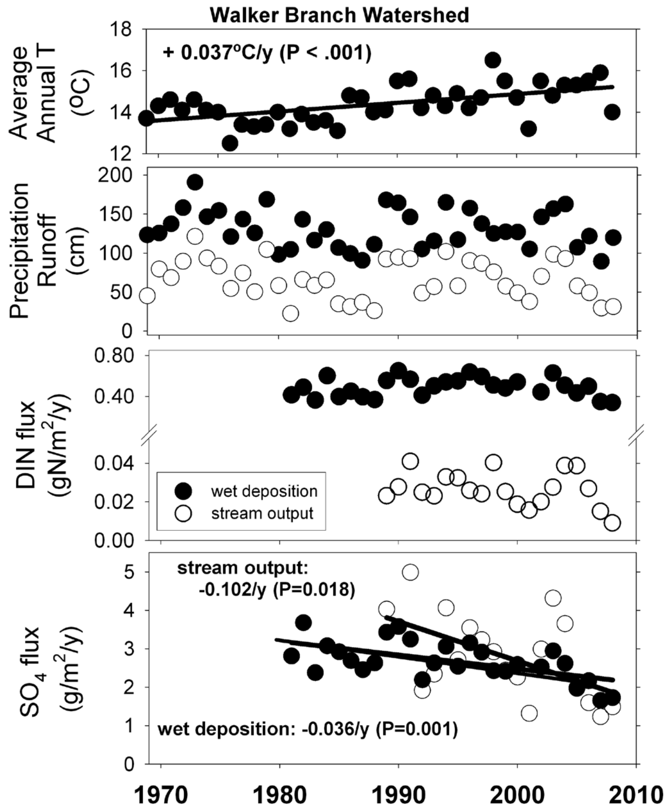

Figure A1-77. Long-term trends in climate, hydrology, and nitrogen and SO4 flux at Walker Branch Watershed (WBW). (Redrawn from Mullholland, 2004, unpublished data). Runoff values are for the East and West Fork catchments combined. Nitrogen and SO_4 flux values are for the West Fork catchment only.

Recently initiated measurements of total dissolved nitrogen (TDN) indicate that TDN output is about twice DIN output. Previous studies indicate that total retention is about 95 percent of inputs. This high rate of nitrogen retention is likely the result of increasing forest biomass and dominance by oaks. Wet SO_4 deposition input and stream SO_4 output are declining. Although stream SO_4 outputs are similar to wet deposition inputs, studies of dry SO_4 deposition in the WBW indicate that total deposition is about twice wet deposition (Tilden Meyers, unpublished data), indicating that SO_4 retention is about 50 percent. The high interannual variability in stream SO_4 output appears to be the result of a strong positive correlation between SO_4 concentration and stream discharge ($r^2 = 0.54$) and interannual variability in stream discharge.

Walnut Gulch Experimental Watershed (WGE) [USDA-ARS]

http://www.tucson.ars.ag.gov/

The Walnut Gulch Experimental Watershed (WGE) was established in the early 1950s to develop knowledge and technology for conserving water and soil in semiarid lands. The watershed is representative of brush- and grass-covered rangeland found in the transition zone between the Chihuahuan and Sonoran Deserts (figure A1-78). Shrubs dominate the lower two-thirds of WGE, including creosotebush (*Larrea divaricata*), whitethorn Acacia (*Acacia constricta*), mariola (*Parthenium incanum*), and tarbush (*Flourensia Cernua*). Grass species dominate the upper third, including black grama (*Bouteloua eriopoda*), sideoats grama (*Bouteloua curtipendula*), three-awn (*Aristida* sp.), and Lehmann lovegrass (*Eragrostis lehmanniana*). Soils are mostly well-drained, calcareous, gravelly loams with large percentages of rock and gravel at the surface. Soil surface rock fragment cover (erosion pavement) can range from nearly 0 percent on shallow slopes to over 70 percent on very steep slopes.

The WGE encompasses 150 square kilometers in southeastern Arizona surrounding the historical town of Tombstone. The precipitation regime is dominated by the North American Monsoon. More than 60 percent of the total annual precipitation comes during July, August, and September, and about 30 percent comes during the 6 months of October through March. Virtually all runoff is generated by summer thunderstorms, and peak flow rates vary greatly with area and year. Cattle grazing is the primary land use, with mining, limited urbanization, and recreation making up the remainder.

Research focus. WGE is the most highly instrumented semiarid experimental watershed in the world and serves as a model for conducting watershed hydrology studies. The critical research issues in the WGE and semiarid rangelands include livestock grazing, water management, erosion control, urbanization, rangeland carbon budget, rangeland rehabilitation, fire, desertification and non-native plant invasion.

Current research focuses on—

- hydrologic processes, climate variability, and water resources for semiarid watershed management, and
- soil erosion, sediment yield, conservation structures, and decision-support systems for sustainable land management.

The anticipated products include—

- better technologies and strategies to manage water, soil, and carbon resources,
- a hydrology and erosion model for rangeland applications, and
- decision-support tools for public land managers.

Figure A1-78. Walnut Gulch Experimental Watershed (WGE USDA-ARS) in Arizona contains both shrublands and grasslands as part of the semiarid landscape. (Photo from USDA-ARS, Southwest Watershed Research Center.)

Wind River Experimental Forest (WIN) [USFS]

http://www.fs.fed.us/pnw/exforests/wind-river/

The Wind River Experimental Forest (WIN) is located in the southwestern Washington Cascades amidst a north-south trending valley bisected by the Wind River. Though the WIN was not established until 1932, USDA Forest Service research in the area began in 1908. The 4,200-ha area comprises two divisions, Trout Creek and Panther Creek. Elevations range between 330 m and 1,300 m. The soils are primarily volcanic in origin.

The nearby Columbia River Gorge affects the Wind River valley's climate, contributing to strong winds year round and cool, wet weather in winter. Precipitation falls as rain or snow during fall, winter, and spring. Summers are warm and dry. Cold air draining into the valley can bring frost almost any time of the year.

WIN is best known for its old-growth forests—more than 400 years in age—of Douglas-fir and western hemlock. Other tree species in the forest include western red cedar, Pacific silver fir, grand fir, and noble fir. Understory trees include Pacific yew, vine maple, Pacific dogwood, and red alder. Younger forests include stands that were established after fires in the late 1840s or the 1902 Yacolt Burn. Numerous plantations were established following timber harvest into the late 1980s.

Research focus. The earliest research focused on how to prevent and control wildfires, how to best regenerate burned and cutover lands, and how to grow seedlings to revegetate thousands of hectares of forest denuded by fire and timber harvesting. The Wind River Arboretum was established in 1912 to study the local success and growth of 150 tree species from all over the world. Permanent growth and yield plots, spacing studies, pruning, fertilization, thinning, and autecology studies provided knowledge on the management and silviculture of Douglas-fir/western hemlock forests in the Pacific Northwest prior to World War II.

In the early 1980s, more ecosystem-oriented studies were conducted, including pollutant monitoring, nutrient cycling, decay of coarse woody debris, and forest gap dynamics. WIN also became one of two focal sites for the Old-Growth Program, whose objectives were defining old-growth Douglas-fir forests, identifying wildlife species associated with these forests, and determining their biological requirements and ecological relationships. In 1994, an 87-meter-tall construction crane was installed in the old-growth forest to study processes operating at the interfaces among vegetation, the atmosphere, and the forest floor (figure A1-79).

Figure A1-79. Wind River Experimental Forest (WIN USFS) in southeastern Washington is dominated by old-growth forests of Douglas fir and western hemlock. A canopy crane constructed in 1994 allows processes to be studied at the interfaces among vegetation, atmosphere, and the forest floor. (Photo from Wind River Canopy Crane Research Facility Image Archive.)

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Appendix 2. Average (standard error) maximum, mean, and minimum air temperature and annual precipitation at each site

(Sites are grouped by ecosystem type. See Appendix 26 for length of record for each station at a site.)

Site code	Air temperature			Precipitation
	Maximum	Mean	Minimum	
	^oC			*cm*
Alpine and arctic				
ARC	-3.7(0.3)	-8.5(0.3)	-14.0(0.4)	32.71(2.1)
GLA	2.2(0.2)*	-0.8(0.2)*	-3.9(0.2)	131.51(9.9)
LVW	6.7(0.2)*	1.5(0.1)	-3.0(0.1)	102.88(3.8)
MCM	-14.2(0.3)	-17.9(0.2)	-21.4(0.3)*	1.38(0.3)*
NWT	7.7(0.2)*	1.8(0.1)*	-4.2(0.1)	68.69(2.1)*
Aridlands				
EOA	15.0(0.1)	7.7(0.1)*	0.4(0.1)*	28.24(1.1)
JRN	24.8(0.1)	14.8(0.1)	4.7(0.1)	26.00(1.0)
RCE	16.4(0.1)*	8.9(0.1)*	1.6(0.1)*	26.80(1.2)
SEV	23.4(0.1)	14.2(0.1)*	5.0(0.1)*	24.37(0.9)
SRE	24.7(0.1)	17.9(0.1)	11.1(0.1)	56.23(1.9)
WGE	25.3(0.1)*	17.5(0.1)*	9.7(0.1)*	35.76(1.0)
Coastal				
CCE	21.2(0.1)	17.5(0.1)*	13.7(0.1)*	25.77(1.2)
FCE	29.4(0.1)	23.9(0.1)*	18.1(0.2)*	140.90(4.8)
GCE	25.8(0.1)	20.5(0.1)	15.1(0.1)	131.19(3.0)
MCR		25.9(0.2)*		209.62(11.8)
PAL	0.8(0.1)	-2.0(0.2)*	-4.0(0.2)*	69.02(3.8)
PIE	15.5(0.1)	9.9(0.1)*	4.3(0.1)*	110.03(2.3)*
SBC	21.6(0.1)	15.8(0.1)*	10.0(0.1)*	43.67(2.7)
VCR	19.7(0.1)*	14.5(0.1)*	9.3(0.1)*	109.71(2.6)
Eastern forests				
BEN	19.7(0.1)	12.9(0.1)*	6.0(0.1)*	121.79(3.0)
CRO	24.3(0.1)*	17.4(0.1)*	10.5(0.1)*	138.60(3.7)
CWT	20.0(0.1)	12.7(0.1)*	5.5(0.1)*	180.33(3.7)
FER	16.9(0.1)*	10.3(0.1)*	3.7(0.1)	127.70(2.3)
HAR	25.6(0.1)	19.7(0.1)*	13.8(0.1)*	176.16(4.4)
HBR	12.0(0.1)*	6.5(0.1)*	1.1(0.1)*	124.32(3.5)
HFR	13.2(0.1)*	7.5(0.1)*	1.8(0.1)*	111.35(3.1)*
LUQ	27.0(0.2)	24.5(0.1)	21.9(0.1)	350.57(15.2)
MAR	10.8(0.1)	4.2(0.1)*	-2.3(0.1)*	66.58(1.3)*
NTL	10.8(0.1)	4.5(0.1)	-1.9(0.1)	79.28(1.3)

Appendix 2. Average (standard error) maximum, mean, and minimum air temperature and annual precipitation at each site—*Continued*

Site code	Air temperature			Precipitation
	Maximum	Mean	Minimum	
	ºC			*cm*
SAN	25.2(0.1)*	18.4(0.1)	11.5(0.1)*	138.25(6.9)
TAL	22.8(0.1)	16.5(0.1)*	10.3(0.1)*	139.96(3.0)*
WBW	20.6(0.1)*	14.4(0.1)*	8.2(0.1)	139.19(3.4)
Temperate grasslands and savannas				
CDR	11.6(0.1)	5.7(0.1)	-0.2(0.1)	69.36(1.1)*
FTK	14.6(0.2)	7.8(0.1)*	1.0(0.1)*	34.05(1.1)
GRL	22.5(0.1)*	15.7(0.1)	8.8(0.1)*	77.01(2.2)*
GSW	25.5(0.2)	19.5(0.1)	13.4(0.1)	90.68(3.0)*
KBS	15.2(0.1)*	9.5(0.1)*	3.8(0.1)*	91.39(2.0)*
KNZ	19.7(0.1)	13.0(0.1)	6.3(0.1)	84.74(2.0)
SGS	17.3(0.2)	9.1(0.1)*	0.8(0.2)*	32.28(1.1)
SPR	22.9(0.1)	15.3(0.1)	7.6(0.1)*	63.30(1.8)
Urban				
BES	18.5(0.1)*	13.1(0.1)	7.7(0.1)	104.66(2.3)
CAP	31.0(0.1)*	21.2(0.1)*	11.3(0.1)*	19.32(0.9)
Western forests				
AND	14.3(0.1)	9.3(0.1)	4.4(0.1)	225.62(5.8)
BLA				
BNZ	3.4(0.4)	-1.3(0.4)	-5.6(0.4)	
CHE	15.0(0.1)*	10.5(0.1)*	5.9(0.1)*	247.19(5.1)
CSP	15.9(0.1)	11.5(0.1)	7.1(0.1)	102.15(3.1)
FRA	13.1(0.2)	6.1(0.1)	-0.9(0.1)*	41.89(1.4)
PRI	13.4(0.1)	6.7(0.1)*	0.1(0.1)*	78.91(1.4)
WIN	15.3(0.1)*	9.0(0.1)	2.6(0.1)*	239.31(6.8)

* Slope is significant ($p < 0.05$) for regression of each variable against time.

Appendix 3. Average (standard error) ice duration, sea level, streamflow, water clarity, and water temperature for sites with data

(Sites are grouped by ecosystem type. See Appendix 26 for length of record for each station at a site.)

Site code	Ice duration *days/year*	Sea level[1] *m*	Streamflow *L/s*	Water clarity *m*	Water temperature *°C*
Alpine and arctic					
ARC	260 (2)		2827.7 (211.5)	4.6 (0.15)	11.0 (0.3)
LVW			165.5 (6.9)		3.7 (0.1)
MCM			749.3 (133.3)		4.0 (0.4)
NWT	267 (4)		166.7 (6.6)		
Aridlands					
RCE			549.6 (69.0)		
WGE			14.1 (1.9)		
Coastal					
CCE		-0.08 (0.01)*		14.2 (0.36)*	17.1 (0.1)*
FCE		-0.07 (0.01)*	3108.0 (549.7)*	1.6 (0.09)	26.2 (0.1)*
GCE		-0.07 (0.01)*	377247.3 (15712.8)		21.4 (0.2)
MCR		-0.001 (0.01)*			
PAL	215(10)				
PIE		-0.06 (0.01)*	1089.9 (42.2)		
SBC		-0.03 (0.004)*	122.2 (26.3)		15.9 (0.1)*
VCR		-0.13 (0.01)*		0.7 (0.04)	
Eastern forests					
BEN			47849.9 (1582.6)		
CWT			4.0 (0.1)		
FER			5.9 (0.2)		
HBR	132 (2)*		3.8 (0.1)		
LUQ		-0.01 (0.01)*	1573.7 (61.0)		
MAR			0.5 (0.03)		
NTL	104 (2)*		141.6 (8.8)*	6.3 (0.13)	13.8 (0.1)*
SAN			41.4 (7.8)*		
WBW			11.4 (0.7)		

Appendix 3. Average (standard error) ice duration, sea level, streamflow, water clarity, and water temperature for sites with data—*Continued*

Site code	Ice duration *days/year*	Sea level[1] *m*	Streamflow *L/s*	Water clarity *m*	Water temperature *°C*
Temperate grasslands and savannas					
GSW			2.9 (0.3)		
KBS	73 (3)		25620.4 (773.0)*		
KNZ			64.7 (10.1)		
Urban					
BES		-0.11 (0.01)*	1160.6 (68.6)		
CAP			27654.4 (2442.5)		
Western forests					
AND			25.7 (0.9)		5.9 (0.1)
BNZ			43.9 (3.0)		
CSP			77.7 (8.5)		10.7 (0.2)
FRA			56.6 (3.1)		
PRI			48302.2 (1487.0)		

[1]Annual mean sea level is defined as the annual arithmetic means of hourly heights relative to the National Tidal Datum Epoch (i.e., the most recent mean sea level datum established by CO-OPS—currently the mean sea level 1983-2001).

* indicates significant slope ($p < 0.05$) for regression of each variable against time.

Appendix 4. Regression coefficients and R^2 values for nine climatic variables for which linear regression against time is significant ($p < 0.05$)

(Sites are grouped by ecosystem type. See Appendix 26 for length of record for each station at a site.)

Site code	Variable	Slope	Y-intercept[1]	R^2
Alpine and arctic				
GLA	Maximum air temperature	0.07	1.6	0.3
	Mean air temperature	0.07	-1.4	0.3
LVW	Maximum air temperature	-0.07	7.5	0.3
MCM	Minimum air temperature	-0.11	-20.1	0.3
	Precipitation	0.21	-0.01	0.4
NWT	Maximum air temperature	0.04	6.5	0.3
	Mean air temperature	0.02	1.2	0.1
	Precipitation	-0.49	86.4	0.2
Aridlands				
EOA	Mean air temperature	0.01	7.3	0.2
	Minimum air temperature	0.02	-0.4	0.2
RCE	Maximum air temperature	0.03	15.7	0.2
	Mean air temperature	0.03	8.2	0.3
	Minimum air temperature	0.03	0.7	0.3
SEV	Mean air temperature	-0.01	14.5	0.1
	Minimum air temperature	-0.01	5.3	0.04
WGE	Maximum air temperature	0.01	24.8	0.05
	Mean air temperature	0.01	16.9	0.2
	Minimum air temperature	0.01	9.0	0.3
Coastal				
CCE	Mean air temperature	0.02	16.8	0.3
	Minimum air temperature	0.03	12.7	0.4
	Sea level	0.002	-0.2	0.8
	Water clarity	-0.11	17.0	0.3
	Water temperature	0.01	16.6	0.2
FCE	Mean air temperature	0.02	23.2	0.4
	Minimum air temperature	0.04	17.1	0.3
	Sea level	0.002	-0.2	0.9
	Streamflow	110.58	564.7	0.2
	Water temperature	-0.03	26.5	0.4
GCE	Sea level	0.003	-0.2	0.8
MCR	Mean air temperature	0.08	24.7	0.6
	Sea level	0.003	-0.04	0.5
PAL	Mean air temperature	0.06	-3.2	0.3
	Minimum air temperature	0.08	-4.9	0.3

Appendix 4. Regression coefficients and R^2 values for nine climatic variables for which linear regression against time is significant ($p < 0.05$)—*Continued*

Site code	Variable	Slope	Y-intercept[1]	R^2
PIE	Mean air temperature	-0.01	10.2	0.05
	Minimum air temperature	-0.01	5.0	0.2
	Precipitation	0.36	87.6	0.3
	Sea level	0.003	-0.2	0.9
SBC	Mean air temperature	0.01	15.2	0.2
	Minimum air temperature	0.02	8.7	0.4
	Sea level	0.001	-0.1	0.3
	Water temperature	0.02	15.5	0.2
VCR	Maximum air temperature	0.02	19.2	0.2
	Mean air temperature	0.03	13.7	0.4
	Minimum air temperature	0.04	8.3	0.5
	Sea level	0.004	-0.3	0.9
Eastern forests				
BEN	Mean air temperature	0.01	12.6	0.1
	Minimum air temperature	0.03	5.3	0.3
CRO	Maximum air temperature	-0.02	25.2	0.3
	Mean air temperature	-0.02	18.2	0.4
	Minimum air temperature	-0.02	11.2	0.2
CWT	Mean air temperature	0.01	12.3	0.1
	Minimum air temperature	0.02	4.9	0.2
FER	Maximum air temperature	-0.02	17.8	0.2
	Mean air temperature	-0.01	10.6	0.1
HAR	Mean air temperature	0.01	19.4	0.1
	Minimum air temperature	0.02	13.3	0.2
HBR	Ice duration	-0.45	140.6	0.2
	Maximum air temperature	0.02	11.5	0.1
	Mean air temperature	0.03	5.8	0.3
	Minimum air temperature	0.03	0.2	0.4
HFR	Maximum air temperature	0.03	12.5	0.3
	Mean air temperature	0.03	6.7	0.4
	Minimum air temperature	0.04	0.8	0.4
	Precipitation	0.59	97.8	0.1
LUQ	Sea level	0.002	-0.1	0.4
MAR	Mean air temperature	0.02	3.4	0.2
	Minimum air temperature	0.03	-3.6	0.3
	Precipitation	0.20	57.0	0.2
NTL	Ice duration	-0.19	117.9	0.2
	Streamflow	2.29	102.7	0.2
	Water temperature	0.06	13.0	0.4
SAN	Maximum air temperature	-0.01	25.7	0.1
	Minimum air temperature	-0.01	11.9	0.1
	Streamflow	4.89	13.5	0.7

Appendix 4. Regression coefficients and R^2 values for nine climatic variables for which linear regression against time is significant ($p < 0.05$)—*Continued*

Site code	Variable	Slope	Y-intercept[1]	R^2
TAL	Mean air temperature	-0.01	17.3	0.1
	Minimum air temperature	-0.02	11.6	0.2
	Precipitation	0.24	123.2	0.1
WBW	Maximum air temperature	0.02	20.0	0.1
	Mean air temperature	0.01	14.0	0.1
Temperate grasslands and savannas				
CDR	Precipitation	0.05	65.1	0.03
FTK	Mean air temperature	0.01	7.3	0.1
	Minimum air temperature	0.02	0.4	0.1
GRL	Maximum air temperature	-0.01	23.1	0.1
	Minimum air temperature	0.02	8.0	0.2
	Precipitation	0.19	68.8	0.1
GSW	Precipitation	0.30	79.9	0.1
KBS	Maximum air temperature	0.02	14.4	0.2
	Mean air temperature	0.02	8.7	0.2
	Minimum air temperature	0.02	3.0	0.2
	Precipitation	0.38	75.2	0.2
	Streamflow	122.12	20,810.5	0.2
SGS	Mean air temperature	0.02	8.3	0.2
	Minimum air temperature	0.04	-0.6	0.3
SPR	Minimum air temperature	0.01	7.1	0.1
Urban				
BES	Maximum air temperature	0.01	18.2	0.1
	Sea level	0.003	-0.3	0.9
CAP	Maximum air temperature	0.01	30.3	0.2
	Mean air temperature	0.02	20.0	0.5
	Minimum air temperature	0.03	9.7	0.5
Western forests				
CHE	Maximum air temperature	0.01	14.7	0.1
	Mean air temperature	0.01	10.1	0.1
	Minimum air temperature	0.01	5.5	0.2
FRA	Minimum air temperature	-0.03	0.01	0.4
PRI	Mean air temperature	0.01	6.4	0.05
	Minimum air temperature	0.01	-0.7	0.2
WIN	Maximum air temperature	-0.02	15.9	0.1
	Minimum air temperature	0.01	2.3	0.1

[1] Y-intercept was calculated for the first year of a dataset, which contains records of one variable over time for one site.

Appendix 5. Annual average (standard error) nitrogen (as nitrate) from various sources at sites with data

(Sites are grouped by ecosystem type. See Appendix 27 for length of record for each station at a site.)

Site code	Precipitation (concentration) *mg/L*	Wet deposition *kg/ha*	Coastal water *μM/L*	Lake *mg/L*	Stream *mg/L*
Alpine and arctic					
ARC	0.06 (0.02)	0.17 (0.01)			0.03 (0.01)*
GLA	0.17 (0.01)	2.00 (0.11)			
LVW	0.17 (0.01)*	1.73 (0.06)			0.28 (0.02)*
MCM				0.14 (0.01)	
NWT	0.21 (0.01)*	3.70 (0.27)*		0.21 (0.01)*	
Aridlands					
JRN	0.42 (0.04)	0.03 (0.002)			
RCE	0.12 (0.01)	0.29 (0.02)			
WGE	0.24 (0.01)	0.85 (0.09)			
Coastal					
CCE			0.2 (0.02)		
FCE	0.12 (0.004)	1.75 (0.08)*	0.3 (0.05)*		
PAL			4.4 (0.15)		
PIE	0.24 (0.01)*	2.64 (0.08)			0.02 (0.001)
SBC			0.4 (0.11)		
VCR	0.23 (0.02)	2.69 (0.19)	0.8 (0.16)		
Eastern forests					
BEN	0.13 (0.01)	2.12 (0.16)			
CRO	0.17 (0.01)	2.33 (0.07)			
CWT	0.15 (0.004)*	2.59 (0.08)*			
FER	0.33 (0.01)*	4.19 (0.18)*			0.78 (0.02)*
HBR	0.28 (0.01)*	3.33 (0.11)*			0.16 (0.02)*
HFR	0.28 (0.01)*	3.46 (0.14)			
LUQ	0.06 (0.004)	1.91 (0.13)			0.14 (0.01)
MAR	0.23 (0.01)*	1.76 (0.05)*			
NTL	0.25 (0.01)*	1.97 (0.09)*		0.01 (0.001)	

Appendix 5. Annual average (standard error) nitrogen (as nitrate) from various sources at sites with data—*Continued*

Site code	Precipitation (concentration) *mg/L*	Wet deposition *kg/ha*	Coastal water *µM/L*	Lake *mg/L*	Stream *mg/L*
SAN	0.17 (0.01)	1.95 (0.08)			
TAL	0.17 (0.01)	2.38 (0.10)			
WBW	0.23 (0.01)*	2.96 (0.10)			0.02 (0.001)
Temperate grasslands and savannas					
CDR	0.29 (0.01)	2.13 (0.18)			
GRL	0.23 (0.01)	2.09 (0.06)			
KBS	0.40 (0.01)*	3.62 (0.14)*			1.11 (0.02)
KNZ	0.28 (0.01)	2.38 (0.08)			0.002 (0.0002)*
SGS	0.32 (0.01)	1.03 (0.05)			
Urban					
BES	0.29 (0.01)*	3.33 (0.16)*			1.98 (0.08)*
CAP	0.66 (0.07)	0.76 (0.15)			0.02 (0.01)*
Western forests					
AND	0.03 (0.001)	0.62 (0.02)			0.001 (0.0001)
BLA	0.06 (0.01)*	0.46 (0.03)			
BNZ	0.03 (0.002)	0.11 (0.01)			
CSP	0.05 (0.003)*	0.47 (0.04)			
FRA	0.21 (0.01)*	3.70 (0.27)*			
PRI	0.09 (0.01)	0.69 (0.05)			

* indicates significant slopes ($p < 0.05$) for regression of each variable against time.

Appendix 6. Regression coefficients and R^2 values for nitrogen (as nitrate) from various sources for which linear regression against time is significant ($p < 0.05$)

(Sites are grouped by ecosystem type. See Appendix 27 for length of record for each station at a site.)

Site code	Source	Slope	Y-intercept[1]	R^2
Alpine and arctic				
ARC	Stream	0.003	0.001	0.4
LVW	Precipitation (concentration)	0.002	0.15	0.2
	Stream	0.009	0.20	0.5
NWT	Lake	0.005	0.15	0.4
	Precipitation (concentration)	0.003	0.17	0.2
	Wet deposition	0.103	2.35	0.3
Coastal				
FCE	Coastal water	0.055	0.12	0.8
	Wet deposition	0.026	1.31	0.3
PIE	Precipitation (concentration)	-0.002	0.27	0.2
Eastern forests				
CWT	Precipitation (concentration)	-0.001	0.17	0.2
	Wet deposition	-0.028	3.07	0.3
FER	Precipitation (concentration)	-0.006	0.43	0.6
FER	Stream	-0.006	0.87	0.2
	Wet deposition	-0.086	5.58	0.6
HBR	Precipitation (concentration)	-0.005	0.36	0.5
	Stream	-0.007	0.31	0.4
	Wet deposition	-0.048	4.14	0.5
HFR	Precipitation (concentration)	-0.006	0.37	0.5
MAR	Precipitation (concentration)	-0.002	0.26	0.2
	Wet deposition	-0.017	2.04	0.3
NTL	Precipitation (concentration)	-0.003	0.29	0.4
	Wet deposition	-0.032	2.47	0.3
WBW	Precipitation (concentration)	-0.002	0.26	0.3
Temperate grasslands and savannas				
KBS	Precipitation (concentration)	-0.005	0.48	0.5
	Wet deposition	-0.062	4.62	0.6
KNZ	Stream	0.0001	0.001	0.3
Urban				
BES	Precipitation (concentration)	-0.007	0.38	0.7
	Stream	-0.073	2.39	0.7
	Wet deposition	-0.084	4.13	0.5
CAP	Stream	0.005	-0.02	0.4

Appendix 6. Regression coefficients and R^2 values for nitrogen (as nitrate) from various sources for which linear regression against time is significant ($p < 0.05$)—*Continued*

Site code	Source	Slope	Y-intercept[1]	R^2
Western forests				
BLA	Precipitation (concentration)	-0.007	0.10	0.5
CSP	Precipitation (concentration)	-0.001	0.06	0.2
FRA	Precipitation (concentration)	0.003	0.17	0.2
	Wet deposition	0.103	2.35	0.3

[1] Y-intercept was calculated for the first year of a dataset, which contains records of one variable over time for one site.

Appendix 7. Annual average (standard error) nitrogen (as ammonium) from various sources at sites with data

(Sites are grouped by ecosystem type. See Appendix 27 for length of record for each station at a site.)

Site code	Precipitation (concentration) *mg/L*	Wet deposition *kg/ha*	Coastal water *μM/L*	Lake *mg/L*	Stream *mg/L*
Alpine and arctic					
ARC	0.08 (0.02)	0.10 (0.01)			0.006 (0.001)*
GLA	0.10 (0.01)*	1.20 (0.08)*			
LVW	0.12 (0.01)*	1.19 (0.06)*			0.014 (0.002)*
MCM				0.01 (0.002)	
NWT	0.11 (0.01)*	1.99 (0.19)*		0.03 (0.004)	
Aridlands					
JRN	0.51 (0.04)*	0.03 (0.002)			
RCE	0.15 (0.01)*	0.38 (0.04)*			
WGE	0.23 (0.02)	0.79 (0.09)			
Coastal					
FCE	0.08 (0.01)	1.24 (0.11)*	5 (1.2)*		
PAL			2 (0.4)		
PIE	0.12 (0.004)*	1.28 (0.06)*			0.002 (0.0002)
SBC			1 (0.1)		
VCR	0.24 (0.07)	2.59 (0.67)	3 (0.5)		
Eastern forests					
BEN	0.11 (0.01)*	1.83 (0.16)*			
CRO	0.20 (0.01)	2.67 (0.18)			
CWT	0.11 (0.005)	1.89 (0.09)			
FER	0.17 (0.005)	2.24 (0.08)			
HBR	0.13 (0.005)	1.57 (0.07)			0.013 (0.001)*
HFR	0.14 (0.01)	1.72 (0.09)			
LUQ	0.03 (0.002)	0.78 (0.07)			0.022 (0.005)*
MAR	0.28 (0.01)	2.10 (0.08)			
NTL	0.27 (0.01)	2.08 (0.11)		0.03 (0.002)	
SAN	0.11 (0.01)*	1.19 (0.07)*			

Appendix 7. Annual average (standard error) nitrogen (as ammonium) from various sources at sites with data—*Continued*

Site code	Precipitation (concentration) *mg/L*	Wet deposition *kg/ha*	Coastal water *µM/L*	Lake *mg/L*	Stream *mg/L*
TAL	0.14 (0.01)	1.97 (0.14)			
WBW	0.15 (0.01)	1.94 (0.09)			0.003 (0.0003)
Temperate grasslands and savannas					
CDR	0.45 (0.02)	3.31 (0.28)			
GRL	0.23 (0.01)*	2.05 (0.08)			
KBS	0.35 (0.01)	3.19 (0.11)			0.017 (0.001)
KNZ	0.31 (0.01)*	2.59 (0.12)*			0.009 (0.002)*
SGS	0.48 (0.02)*	1.53 (0.08)			
Urban					
BES	0.19 (0.01)	2.19 (0.10)			
CAP	0.97 (0.14)	1.07 (0.21)			0.018 (0.003)
Western forests					
AND	0.02 (0.001)	0.33 (0.02)			0.009 (0.001)
BLA	0.04 (0.005)	0.35 (0.04)			
BNZ	0.02 (0.005)				
CSP	0.04 (0.003)	0.34 (0.03)			
FRA	0.11 (0.01)*	1.99 (0.19)*			
PRI	0.10 (0.005)	0.76 (0.02)			

* indicates significant slopes ($p < 0.05$) for regression of each variable against time.

Appendix 8. Regression coefficients and R^2 values for nitrogen (as ammonium) from various sources for which linear regression against time is significant ($p < 0.05$)

(Sites are grouped by ecosystem type. See Appendix 27 for length of record for each station at a site.)

Site code	Source	Slope	Y-intercept[1]	R^2
Alpine and arctic				
ARC	Stream	-0.001	0.01	0.3
GLA	Precipitation (concentration)	0.003	0.07	0.4
	Wet deposition	0.037	0.75	0.5
LVW	Precipitation (concentration)	0.004	0.07	0.6
	Stream	-0.001	0.02	0.4
	Wet deposition	0.027	0.83	0.4
NWT	Precipitation (concentration)	0.003	0.07	0.2
	Wet deposition	0.075	1.02	0.3
Aridlands				
JRN	Precipitation (concentration)	0.020	0.25	0.7
RCE	Precipitation (concentration)	0.004	0.10	0.2
	Wet deposition	0.010	0.25	0.2
Coastal				
FCE	Coastal water	1.325	0.60	0.7
	Wet deposition	0.032	0.70	0.3
PIE	Precipitation (concentration)	0.002	0.09	0.3
	Wet deposition	0.025	0.94	0.5
Eastern forests				
BEN	Precipitation (concentration)	0.002	0.08	0.3
	Wet deposition	0.055	1.15	0.2
HBR	Stream	-0.0004	0.02	0.4
LUQ	Stream	-0.002	0.04	0.3
SAN	Precipitation (concentration)	0.003	0.06	0.6
	Wet deposition	0.032	0.76	0.5
Temperate grasslands and savannas				
GRL	Precipitation (concentration)	0.003	0.18	0.2
KNZ	Precipitation (concentration)	0.005	0.24	0.4
	Stream	0.002	-0.01	0.6
	Wet deposition	0.051	1.85	0.4
SGS	Precipitation (concentration)	0.008	0.35	0.3
Western forests				
FRA	Precipitation (concentration)	0.003	0.07	0.2
	Wet deposition	0.075	1.02	0.3

[1] Y-intercept was calculated for the first year of a dataset, which contains records of one variable over time for one site.

Appendix 9. Annual average (standard error) sulfur (as sulfate) from various sources at sites with data

(Sites are grouped by ecosystem type. See Appendix 27 for length of record for each station at a site.)

Site code	Precipitation (concentration) *mg/L*	Wet deposition *kg/ha*	Lake *mg/L*	Stream *mg/L*
Alpine and arctic				
ARC	0.08 (0.01)*			
GLA	0.18 (0.01)*	2.15 (0.10)		
LVW	0.18 (0.01)*	1.80 (0.10)*		0.7 (0.03)*
MCM			58 (2.83)	
NWT	0.18 (0.01)*	3.18 (0.17)	2 (0.19)*	
Aridlands				
JRN	0.60 (0.05)	0.04 (0.003)*		
RCE	0.12 (0.01)*	0.30 (0.03)		
WGE	0.24 (0.02)	0.82 (0.09)		
Coastal				
FCE	0.24 (0.004)	3.55 (0.13)*		
PIE	0.60 (0.03)*	6.59 (0.28)*		
VCR	0.62 (0.06)	4.71 (0.52)		
Eastern forests				
BEN	0.38 (0.02)	6.29 (0.45)		
CRO	0.35 (0.01)*	4.81 (0.18)		
CWT	0.40 (0.02)*	6.85 (0.33)*		
FER	0.81 (0.04)*	10.47 (0.60)*		1.5 (0.03)
HBR	0.51 (0.03)*	6.19 (0.32)*		1.8 (0.04)*
HFR	0.51 (0.03)*	6.30 (0.30)*		
LUQ	0.26 (0.01)	8.22 (0.47)		0.7 (0.03)
MAR	0.32 (0.02)*	2.45 (0.14)*		
NTL	0.38 (0.02)*	2.99 (0.22)*	1 (0.03)*	
SAN	0.44 (0.01)	4.95 (0.19)		
TAL	0.33 (0.01)*	4.69 (0.19)*		
WBW	0.69 (0.02)*	8.96 (0.33)*		0.8 (0.02)
Temperate grasslands and savannas				
CDR	0.36 (0.01)	2.63 (0.19)		
GRL	0.37 (0.01)	3.42 (0.12)*		
KBS	0.77 (0.04)*	7.05 (0.46)*		6.6 (0.05)
KNZ	0.41 (0.01)*	3.42 (0.15)*		
SGS	0.33 (0.02)*	1.07 (0.08)*		
Urban				
BES	0.67 (0.03)*	7.28 (0.35)*		8.6 (0.21)
CAP	0.89 (0.27)	5.07 (2.28)		22.6 (2.01)*

Appendix 9. Annual average (standard error) sulfur (as sulfate) from various sources at sites with data—*Continued*

Site code	Precipitation (concentration) *mg/L*	Wet deposition *kg/ha*	Lake *mg/L*	Stream *mg/L*
Western forests				
AND	0.06 (0.002)*	1.20 (0.05)		0.1 (0.003)
BLA	0.05 (0.005)	0.39 (0.04)		
BNZ	0.06 (0.004)	0.23 (0.02)		
CSP	0.08 (0.005)*	0.75 (0.07)*		
FRA	0.18 (0.01)*	3.18 (0.17)		
PRI	0.07 (0.005)	0.54 (0.02)		

* indicates significant slopes ($p < 0.05$) for regression of each variable against time.

Appendix 10. Regression coefficients and R^2 values for sulfur (sulfate) from various sources for which linear regression against time is significant ($p < 0.05$)

(Sites are grouped by ecosystem type. See Appendix 27 for length of record for each station at a site.)

Site code	Source	Slope	Y-intercept[1]	R^2
Alpine and arctic				
ARC	Precipitation (concentration)	-0.007	0.1	0.3
GLA	Precipitation (concentration)	-0.002	0.2	0.3
LVW	Precipitation (concentration)	-0.003	0.2	0.5
	Stream	0.018	0.6	0.4
	Wet deposition	-0.046	2.4	0.5
NWT	Lake	0.091	1.0	0.5
	Precipitation (concentration)	-0.004	0.2	0.6
Aridlands				
JRN	Wet deposition	-0.001	0.1	0.4
RCE	Precipitation (concentration)	-0.003	0.2	0.2
Coastal				
FCE	Wet deposition	0.037	2.9	0.2
PIE	Precipitation (concentration)	-0.015	0.8	0.6
	Wet deposition	-0.127	8.4	0.5
Eastern forests				
CRO	Precipitation (concentration)	-0.003	0.4	0.2
CWT	Precipitation (concentration)	-0.007	0.5	0.4
	Wet deposition	-0.158	9.6	0.6
FER	Precipitation (concentration)	-0.022	1.2	0.7
	Wet deposition	-0.293	15.2	0.6
HBR	Precipitation (concentration)	-0.015	0.8	0.8
	Stream	-0.022	2.2	0.9
	Wet deposition	-0.157	8.8	0.7
HFR	Precipitation (concentration)	-0.017	0.8	0.7
	Wet deposition	-0.135	8.3	0.4
MAR	Precipitation (concentration)	-0.009	0.5	0.7
	Wet deposition	-0.075	3.7	0.7
NTL	Lake	-0.016	1.2	0.7
	Precipitation (concentration)	-0.013	0.6	0.8
	Wet deposition	-0.120	4.8	0.7
TAL	Precipitation (concentration)	-0.005	0.4	0.4
	Wet deposition	-0.050	5.4	0.2
WBW	Precipitation (concentration)	-0.013	0.9	0.7
	Wet deposition	-0.120	10.8	0.3

Appendix 10. Regression coefficients and R^2 values for sulfur (sulfate) from various sources for which linear regression against time is significant ($p < 0.05$)—*Continued*

Site code	Source	Slope	Y-intercept[1]	R^2
Temperate grasslands and savannas				
GRL	Wet deposition	-0.051	4.1	0.3
KBS	Precipitation (concentration)	-0.023	1.1	0.9
	Wet deposition	-0.231	10.8	0.8
KNZ	Precipitation (concentration)	-0.006	0.5	0.6
	Wet deposition	-0.039	4.0	0.2
SGS	Precipitation (concentration)	-0.007	0.4	0.3
	Wet deposition	-0.031	1.6	0.4
Urban				
BES	Precipitation (concentration)	-0.017	0.9	0.7
	Wet deposition	-0.170	8.9	0.4
CAP	Stream	-1.215	29.9	0.4
Western forests				
AND	Precipitation (concentration)	-0.001	0.1	0.3
CSP	Precipitation (concentration)	-0.002	0.1	0.5
	Wet deposition	-0.022	1.1	0.2
FRA	Precipitation (concentration)	-0.004	0.2	0.6

[1] Y-intercept was calculated for the first year of a dataset, which contains records of one variable over time for one site.

Appendix 11. Annual average (standard error) chloride from various sources at sites with data

(Sites are grouped by ecosystem type. See Appendix 27 for length of record for each station at a site.)

Site code	Precipitation (concentration) *mg/L*	Wet deposition *kg/ha*	Lake *mg/L*	Stream *mg/L*
Alpine and arctic				
ARC	0.34 (0.17)			
GLA	0.08 (0.01)*	0.98 (0.09)*		
LVW	0.07 (0.01)*	0.72 (0.08)*		0.2 (0.01)*
MCM			707.6 (61.04)*	
NWT	0.08 (0.01)*	1.38 (0.12)	0.1 (0.01)	
Aridlands				
JRN	0.56 (0.07)	0.02 (0.002)		
RCE	0.10 (0.01)*	0.26 (0.03)*		
WGE	0.12 (0.01)*	0.45 (0.07)		
Coastal				
FCE	0.93 (0.04)	13.62 (0.72)		
PIE	0.61 (0.03)*	6.75 (0.38)		
VCR	3.51 (0.54)	42.19 (6.26)		
Eastern forests				
BEN	0.09 (0.01)	1.52 (0.12)		
CRO	0.25 (0.01)	3.40 (0.19)		
CWT	0.17 (0.01)	2.97 (0.17)*		
FER	0.11 (0.01)*	1.46 (0.08)*		0.5 (0.01)*
HBR	0.16 (0.01)*	1.97 (0.15)		0.5 (0.01)*
HFR	0.23 (0.01)	2.90 (0.19)		
LUQ	2.71 (0.10)	85.16 (4.92)		8.5 (0.11)
MAR	0.07 (0.01)*	0.51 (0.04)*		
NTL	0.07 (0.01)*	0.54 (0.05)*	4.7 (0.29)*	
SAN	0.40 (0.02)	4.56 (0.32)		
TAL	0.24 (0.01)	3.41 (0.17)		
WBW	0.19 (0.01)*	2.54 (0.12)		0.9 (0.03)
Temperate grasslands and savannas				
CDR	0.07 (0.003)	0.50 (0.04)		
GRL	0.18 (0.01)	1.66 (0.13)*		
KBS	0.14 (0.02)	1.29 (0.22)		11.2 (0.13)
KNZ	0.11 (0.004)*	0.92 (0.05)		
SGS	0.09 (0.01)*	0.30 (0.02)*		
Urban				
BES	0.40 (0.03)*	4.16 (0.23)		119.3 (12.20)
CAP	0.89 (0.14)	1.24 (0.20)		386.6 (29.70)

Appendix 11. Annual average (standard error) chloride from various sources at sites with data—*Continued*

Site code	Precipitation (concentration) *mg/L*	Wet deposition *kg/ha*	Lake *mg/L*	Stream *mg/L*
Western forests				
AND	0.31 (0.01)	6.88 (0.43)		1.0 (0.04)
BLA	0.05 (0.003)	0.42 (0.04)*		
BNZ	0.04 (0.003)*	0.16 (0.03)*		
CSP	0.58 (0.04)	5.54 (0.60)		
FRA	0.08 (0.01)*	1.38 (0.12)		
PRI	0.05 (0.003)	0.38 (0.03)		

* indicates significant slopes ($p < 0.05$) for regression of each variable against time.

Appendix 12. Regression coefficients and R^2 values for chloride from various sources for which linear regression against time is significant ($p < 0.05$)

(Sites are grouped by ecosystem type. See Appendix 27 for length of record for each station.)

Site code	Source	Slope	Y-intercept[1]	R^2
Alpine and arctic				
GLA	Precipitation (concentration)	-0.004	0.1	0.7
	Wet deposition	-0.038	1.4	0.4
LVW	Precipitation (concentration)	-0.002	0.1	0.3
	Stream	0.003	0.2	0.4
	Wet deposition	-0.026	1.1	0.3
MCM	Lake	30.382	479.8	0.3
NWT	Precipitation (concentration)	-0.003	0.1	0.5
Aridlands				
RCE	Precipitation (concentration)	-0.004	0.1	0.4
	Wet deposition	-0.010	0.4	0.4
WGE	Precipitation (concentration)	-0.006	0.2	0.5
Coastal				
PIE	Precipitation (concentration)	-0.008	0.7	0.2
Eastern forests				
CWT	Wet deposition	-0.046	3.8	0.2
FER	Precipitation (concentration)	-0.002	0.2	0.6
	Stream	-0.005	0.6	0.4
	Wet deposition	-0.032	2.0	0.5
HBR	Precipitation (concentration)	-0.003	0.2	0.2
	Stream	-0.003	0.5	0.3
MAR	Precipitation (concentration)	-0.003	0.1	0.6
	Wet deposition	-0.022	0.9	0.7
NTL	Lake	0.188	2.2	0.96
	Precipitation (concentration)	-0.002	0.1	0.5
	Wet deposition	-0.022	0.9	0.6
WBW	Precipitation (concentration)	-0.002	0.2	0.2
Temperate grasslands and savannas				
GRL	Wet deposition	-0.043	2.2	0.2
KNZ	Precipitation (concentration)	-0.002	0.1	0.3
SGS	Precipitation (concentration)	-0.003	0.1	0.6
	Wet deposition	-0.011	0.5	0.6
Urban				
BES	Precipitation (concentration)	-0.008	0.5	0.2

Appendix 12. Regression coefficients and R^2 values for chloride from various sources for which linear regression against time is significant ($p < 0.05$)—*Continued*

Site code	Source	Slope	Y-intercept[1]	R^2
Western forests				
BLA	Wet deposition	0.031	0.3	0.5
BNZ	Precipitation (concentration)	-0.002	0.1	0.4
	Wet deposition	-0.013	0.3	0.6
FRA	Precipitation (concentration)	-0.003	0.1	0.5

[1] Y-intercept was calculated for the first year of a dataset, which contains records of one variable over time for one site.

Appendix 13. Annual average (standard error) calcium from various sources at sites with data

(Sites are grouped by ecosystem type. See Appendix 27 for length of record for each station at a site.)

Site code	Precipitation (concentration)	Wet deposition	Lake	Stream
	mg/L	*kg/ha*	*mg/L*	*mg/L*
Alpine and arctic				
ARC	0.19 (0.07)			
GLA	0.20 (0.02)	2.4 (0.21)*		
LVW	0.19 (0.02)	1.8 (0.17)		2 (0.04)*
MCM			79 (3.8)	
NWT	0.20 (0.01)	3.6 (0.37)*	4 (0.2)*	
Aridlands				
JRN	1.36 (0.18)*	0.1 (0.01)		
RCE	0.14 (0.01)*	0.3 (0.03)*		
WGE	0.24 (0.02)	0.8 (0.10)		
Coastal				
FCE	0.13 (0.01)*	1.9 (0.10)		
PIE	0.08 (0.01)	0.8 (0.06)		
VCR	0.16 (0.02)	1.9 (0.22)		
Eastern forests				
BEN	0.04 (0.002)*	0.7 (0.05)*		
CRO	0.11 (0.01)	1.5 (0.08)		
CWT	0.06 (0.004)	1.0 (0.06)*		
FER	0.15 (0.01)*	1.9 (0.13)*		2 (0.03)
HBR	0.06 (0.004)*	0.7 (0.05)*		1 (0.04)*
HFR	0.06 (0.003)	0.7 (0.04)		
LUQ	0.14 (0.005)	4.4 (0.23)		4 (0.13)*
MAR	0.20 (0.01)	1.5 (0.06)*		
NTL	0.19 (0.01)	1.5 (0.08)*	10 (0.2)*	
SAN	0.09 (0.004)	1.0 (0.05)		
TAL	0.09 (0.01)*	1.3 (0.08)*		
WBW	0.11 (0.01)	1.5 (0.06)		24 (0.57)
Temperate grasslands and savannas				
CDR	0.31 (0.02)	2.3 (0.23)		
GRL	0.31 (0.02)	2.7 (0.15)		
KBS	0.22 (0.01)*	2.0 (0.09)*		70 (0.21)
KNZ	0.36 (0.01)	3.0 (0.14)*		
SGS	0.28 (0.02)	0.9 (0.06)		

Appendix 13. Annual average (standard error) calcium from various sources at sites with data—*Continued*

Site code	Precipitation (concentration)	Wet deposition	Lake	Stream
	mg/L	*kg/ha*	*mg/L*	*mg/L*
Urban				
BES	0.08 (0.004)*	0.8 (0.03)	--	--
CAP	1.04 (0.13)	--	--	58 (3.42)
Western forests				
AND	0.03 (0.001)*	0.6 (0.04)	--	3 (0.04)
BLA	0.03 (0.002)	0.2 (0.03)	--	--
BNZ	0.03 (0.002)*	0.1 (0.01)	--	--
CSP	0.03 (0.002)*	0.3 (0.03)	--	--
FRA	0.20 (0.01)	3.6 (0.37)*	--	--
PRI	0.06 (0.004)	0.4 (0.02)	--	--

* Slope is significant ($p < 0.05$) for regression of each variable against time.

Appendix 14. Regression coefficients and R^2 values for calcium from various sources for which linear regression against time is significant ($p < 0.05$)

(Sites are grouped by ecosystem type. See Appendix 27 for length of record for each station at a site.)

Site code	Source	Slope	Y-intercept[1]	R^2
Alpine and arctic				
GLA	Wet deposition	0.064	1.6	0.2
LVW	Stream	0.021	1.7	0.4
NWT	Lake	0.117	2.2	0.5
	Wet deposition	0.110	2.1	0.2
Aridlands				
JRN	Precipitation (concentration)	0.069	0.6	0.3
RCE	Precipitation (concentration)	-0.004	0.2	0.3
	Wet deposition	-0.012	0.5	0.4
Coastal				
FCE	Precipitation (concentration)	-0.002	0.2	0.3
Eastern forests				
BEN	Precipitation (concentration)	0.001	0.03	0.2
	Wet deposition	0.020	0.4	0.3
CWT	Wet deposition	-0.014	1.3	0.2
FER	Precipitation (concentration)	-0.005	0.2	0.6
	Wet deposition	-0.060	2.9	0.6
HBR	Precipitation (concentration)	-0.002	0.1	0.4
	Stream	-0.019	1.4	0.9
	Wet deposition	-0.017	1.0	0.3
LUQ	Stream	0.051	3.8	0.3
MAR	Wet deposition	-0.015	1.7	0.2
NTL	Lake	0.098	8.8	0.8
	Wet deposition	-0.021	1.8	0.2
TAL	Precipitation (concentration)	0.002	0.1	0.3
	Wet deposition	0.030	0.9	0.4
Temperate grasslands and savannas				
KBS	Precipitation (concentration)	-0.003	0.3	0.3
	Wet deposition	-0.031	2.5	0.3
KNZ	Wet deposition	0.044	2.4	0.2
Urban				
BES	Precipitation (concentration)	-0.001	0.1	0.3

Appendix 14. Regression coefficients and R^2 values for calcium from various sources for which linear regression against time is significant ($p < 0.05$)—*Continued*

Site code	Source	Slope	Y-intercept[1]	R^2
Western forests				
AND	Precipitation (concentration)	-0.0004	0.03	0.2
BNZ	Precipitation (concentration)	0.001	0.02	0.5
CSP	Precipitation (concentration)	-0.001	0.04	0.2
FRA	Wet deposition	0.110	2.1	0.2

[1] Y-intercept was calculated for the first year of a dataset, which contains records of one variable over time for one site.

Appendix 15. Human population and economy variables in 2000 for the focal county of each site, as grouped by ecosystem type

Site code	Focal county	Total population	Population density	Urban population	Employment by sector			
					Commercial[1]	Farming[2]	Manufacturing[3]	Service[4]
			#/km²	*% total population*				
Alpine and arctic								
ARC	North Slope, AK	7,385	0	59	4.6	0.0	-	7.3
GLA	Albany, WY	32,014	3	88	5.7	0.5[2]	1.3	6.1[4]
LVW	Larimer, CO	251,494	37	86	7.1	0.3[2]	3.6	4.7[4]
MCM	-	-	-	-	-	-	-	-
NWT	Boulder, CO	291,288	152	91	8.4	0.1	5.6	6.7
Aridlands								
EOA	Harney, OR	7,609	0	57	4.4	3.8[2]	4.2[3]	2.3[4]
JRN	Dona Ana, NM	174,682	18	80	4.4	0.4	1.1	7.1
RCE	Owyhee, ID	10,644	1	26	3.6	4.6[2]	5.6	1.1[4]
SEV	Socorro, NM	18,078	1	47	2.9	0.8	0.6[3]	7.0
SRE	Pima, AZ	843,746	36	92	6.1	0.1	1.9	4.1[4]
WGE	Santa Cruz, AZ	38,381	12	68	11.3	0.3[2]	1.9[3]	3.8[4]
Coastal								
CCE	San Diego, CA	2,813,833	259	96	6.3	0.1	2.7	7.1
FCE	Miami-Dade, FL	2,253,362	447	99	8.4	0.1	2.3	6.9
GCE	McIntosh, GA	10,847	10	26	7.2	0.1	3.3[3]	7.2
MCR	-	-	-	-	-	-	-	-
PAL	-	-	-	-	-	-	-	-
PIE	Essex, MA	723,419	558	95	7.0	0.0	5.1	6.6
SBC	Santa Barbara, CA	399,347	56	95	6.0	0.3	2.1	7.7
VCR	Northampton, VA	13,093	24	-	4.5	0.7	10.7[3]	7.9

Appendix 15. Human population and economy variables in 2000 for the focal county of each site, as grouped by ecosystem type—*Continued*

Site code	Focal county	Total population	Population density	Urban population	Employment by sector			
					Commercial[1]	Farming[2]	Manufacturing[3]	Service[4]
			#/km²	*% total population*				
Eastern forests								
BEN	Buncombe, NC	206,330	122	71	6.7	0.1	7.8[3]	7.6
CRO	Ashley, AR	24,209	10	49	4.0	0.7[2]	13.4	1.2[4]
CWT	Macon, NC	29,811	22	19	6.6	0.2	4.1	6.7
FER	Tucker, WV	7,321	7	-	3.6	0.4	5.2[3]	9.1
HAR	Harrison, MS	189,601	126	79	6.9	0.1[2]	1.9	5.3[4]
HBR	Grafton, NH	81,743	18	35	8.9	0.2	6.4	8.3
HFR	Worcester, MA	750,963	192	81	6.5	0.1	5.3	6.8
LUQ	Rio Grande, PR	52,362	333	96	1.7	-	2.8	4.6
MAR	Itasca, MN	43,992	6	19	6.4	0.4[2]	4.5	3.2[4]
NTL	Dane, WI	426,526	137	85	9.8	0.4	4.6	7.4
SAN	Berkeley, SC	142,651	50	66	3.1	0.1[2]	3.3	1.7[4]
TAL	Lafayette, MS	38,744	24	50	6.0	0.4[2]	4.5	4.5[4]
WBW	Roane, TN	51,910	56	51	4.3	0.4[2]	3.2	2.1[4]
Temperate grasslands and savannas								
CDR	Anoka, MN	298,084	271	86	6.4	0.1	6.0	6.6
FTK	Custer, MT	11,696	1	83	7.8	2.2[2]	0.9[3]	5.4[4]
GRL	Grady, OK	45,516	16	34	4.7	1.8[2]	5.4	2.2[4]
GSW	Bell, TX	237,974	87	82	4.6	0.3[2]	2.6	3.0[4]
KBS	Kalamazoo, MI	238,603	164	80	9.3	0.1	6.7	7.9
KNZ	Riley, KS	62,843	40	85	6.0	0.6	0.7	8.8
SGS	Weld, CO	180,936	18	72	5.4	0.9	4.7	7.1
SPR	Woodward, OK	18,486	6	60	7.6	2.1[2]	2.1	3.3[4]
Urban								
BES	Baltimore City, MD[5]	651,154	3,104	100	5.5	0.0	3.2	7.9
CAP	Maricopa, AZ	3,072,149	129	97	7.4	0.1	3.2	6.8

Appendix 15. Human population and economy variables in 2000 for the focal county of each site, as grouped by ecosystem type—*Continued*

Site code	Focal county	Total population	Population density	Urban population	Employment by sector			
					Commercial[1]	Farming[2]	Manufacturing[3]	Service[4]
			#/km²	*% total population*				
Western forests								
AND	Lane, OR	322,959	27	81	7.8	0.2	4.6	7.6
BLA	Lassen, CA	33,828	3	41	3.2	0.6[2]	2.1[3]	2.3[4]
BNZ	Fairbanks North Star, AK	82,840	4	70	6.4	0.1	0.4[3]	6.5
CHE	Tillamook, OR	24,262	9	24	4.9	1.2[2]	4.5	4.6[4]
CSP	Mendocino, CA	86,265	10	54	6.7	0.7[2]	3.8	4.3[4]
FRA	Grand, CO	12,442	3	0	6.8	1.1[2]	1.1[3]	12.3
PRI	Bonner, ID	36,835	8	23	7.6	0.8[2]	4.6	4.1[4]
WIN	Skamania, WA	9,872	2	0[6]	1.5	0.3[2]	4.6[3]	2.4[4]

[1] Data from 1997. The 1997 total population size is interpolated from long-term data for the county.
[2] With footnote, data are from 1992; without footnote, data are from 2000. The 1992 total population size is interpolated from long-term data for the county.
[3] With footnote, data are from 1992; without footnote, data are from 1997. The 1992 and 1997 total population sizes are interpolated from long-term data for the county.
[4] With footnote, data are from 1997; without footnote, data are from 2000. The 1997 total population size is interpolated from long-term data for the county.
[5] The focal county is Baltimore City, not Baltimore County.
[6] Percentage of urban population in 1990, not 2000.
- No available data.

Appendix 16. Annual average (standard error) aboveground net primary production (ANPP) at sites with data

(Multiple stations are given if possible. Sites are grouped by ecosystem type. See appendix 28 for length of record for each station.)

Site code	Station	ANPP[1]
Alpine and arctic		
ARC	Control ANPP plots	156 (20)
	Nitrogen-fertilized ANPP plots	306 (33)*
NWT	Dry meadow plots at Saddle Location	204 (13)*
	Moist meadow plots at Saddle Location	208 (8)*
	Wet meadow plots at Saddle Location	171 (8)*
Aridlands		
JRN	Creosote Study Sites	84 (6)
	Grassland Study Sites	130 (17)*
	Mesquite Study Sites	113 (20)*
	Playa Study Sites	204 (36)
	Tarbush Study Sites	79 (8)
SEV	Blue Grama Study Site	83 (17)
	Five-Points Grass Study Site	93 (21)*
	Five-Points *Larrea* Study Site	63 (6)
Coastal		
PIE	*Spartina alterniflora*-dominated salt marsh at Law's Point, Rowley River, Plum Island Environment, MA	725 (137)
	Spartina patens-dominated salt marsh at Law's Point, Rowley River, Plum Island Environment, MA	1183 (92)
	Spartina alterniflora-dominated salt marsh at Goat Island, North Inlet, Georgetown, SC	913 (58)*
Eastern forests		
HBR	Unknown	705 (8)*
HFR	Little Prospect Hill at Harvard Forest, trees only; unit: Mg carbon/ha	3 (0.2)
Temperate grasslands and savannas		
CDR	Unknown	277 (22)*
FTK	Lysimeter 1	430 (83)
	Lysimeter 8	231 (29)
	Treatment 8, never plowed, 200 m south of the others, serves as a historical control for soil organic matter studies	302 (44)
	Treatment SF, old field successional community, never tilled	197 (19)*
KBS	Treatment 7, native successional treatment, abandoned after spring plowing in 1989	501 (39)*

Appendix 16. Annual average (standard error) aboveground net primary production (ANPP) at sites with data—*Continued*

Site code	Station	ANPP[1]
KNZ	Watershed 020b, burned every 20 years, on shallow Florence soils	338 (15)
	Watershed 020b, burned every 20 years, on deep Tully soils	424 (19)
SGS	ESA Control 1	92 (7)*
	Owl Creek, coarse texture soil	104 (11)*
	Sec 25, fine texture soil	62 (7)
Western forests		
AND	Reference Stand 2, tree boles only	326 (47)
	Reference Stand 29. tree boles only	566 (96)
BNZ	Unknown	300 (16)

[1] Unit is g/m^2 unless otherwise specified.

* Linear regression of the variable against time is significant ($p < 0.05$) and the trend appears linear.

Appendix 17. Other measures of average (standard error) terrestrial production at sites with data
(Multiple stations are given if possible. Sites are grouped by ecosystem type. See Appendix 28 for length of record for each station.)

Site code	Variable	Station	Terrestrial production
Eastern forests			
BEN	DBH[1] (cm)	Mixed hardwood plots	28 (1)
		Yellow Poplar plots	40 (2)
CRO	Production volume (m^3/ha), pine	Clearcut logging stands	184 (55)
		Diameter limit logging stands	183 (40)
		Heavy seedtree logging stands	200 (50)
		Selection logging stands	154 (31)
	Seed production (#/ha), pine	Unknown	
	Viable seed		1175 (307)
	Void		641 (127)
	Total		1816 (429)
HAR	DBH (cm), *Pinus palustris*	North plantation	15 (5)
		South plantation	16 (5)
	Height (m), *P. palustris*	North plantation	11 (5)
		South plantation	11 (5)
HBR	DBH (cm)	Vegetation zones 2 and 3 at watershed 6	16 (1)
		Vegetation zone 5 at watershed 6	20 (2)
		Vegetation zone 4 at watershed 6	18 (1)
		Vegetation zone 1 at watershed 6	15 (1)
HFR		Lyford Blocks within the Prospect Hill Tract	15 (0.4)
Western forests			
CHE	DBH (cm)	HSGY Study Plots	
	Picea sitchensis		71 (2)
	Pseudotsuga menziesii		59 (2)*
	Tsuga heterophylla		34 (4)

[1] DBH: diameter at breast height of trees.
* indicates that the linear regression of the variable against time is significant ($p < 0.05$) and the trend appears linear.

Appendix 18. Average (standard error) aquatic production at sites with data

(Multiple stations are given if possible. Sites are grouped by ecosystem type. See Appendix 28 for length of record for each station.)

Site code	Variable	Station	Aquatic production
Alpine and arctic			
ARC	Chlorophyll a (mg/m^2)	Fertilized reach of Kuparuk River	13 (4)
		Reference reach of Kuparuk River	3 (0.4)
	Chlorophyll a (µg/L)	Toolik Lake	1 (0.1)
MCM	Primary production (g carbon/m^2/yr)	East Lake Bonney	5 (0.3)
		West Lake Bonney	8 (1)
Coastal			
CCE	Chlorophyll a (µg/L)	Ohman Region: subset of CalCOFI stations inshore and nearshore in the Southern California Bight region; CalCOFI lines 80-93, stations from shore offshore to station 70	1 (0.1)*
	Primary production (g carbon/m^2/yr)	Ohman Region: subset of CalCOFI stations inshore and nearshore in the Southern California Bight region; CalCOFI lines 80-93, stations from shore offshore to station 70	363 (4)
FCE	Net primary production (g carbon/m^2/yr)	Shark River Slough sites 1, 2, and 3, Epiphyton substrate	40 (11)
		Shark River Slough sites 1, 2, and 3, Mat substrate	72 (25)
		Shark River Slough sites 1, 2, and 3, Periphyton substrate	49 (15)
MCR	Chlorophyll a (µg/L)	SeaWiFS data for Moorea Coral Reef Vicinity, area for chlorophyll and SST data	21 (1)
PAL	Chlorophyll a (mg/m^2)	Palmer Station B	123 (24)
	Primary production (g carbon/m^2/yr)	Palmer Station	169 (21)
Eastern forests			
NTL	Primary production, hypsometrically weighted (g carbon/m^2/yr)	Crystal Lake, epilimnion	30 (3)
		Sparkling Lake, epilimnion	32 (3)
		Trout Lake, epilimnion	45 (4)

* Linear regression of the variable against time is significant ($p < 0.05$) and the trend appears linear.

Appendix 19. Average (standard error) biomass of primary producers (plants, algae) for sites with data

(Multiple stations are given if possible. Sites are grouped by ecosystem type. See Appendix 28 for length of record for each station.)

Site code	Taxon	Station	Biomass[1]
Alpine and arctic			
ARC		Tussock Tundra 1981 Plots,	
	Betula nana (Dwarf birch)	control	81 (18)
		fertilized	410 (146)
	Eriophorum vaginatum	control	56 (12)
	(Tussock cottongrass)	fertilized	55 (27)
	Ledum palustre	control	79 (6)
	(Marsh labrador tea)	fertilized	48 (13)
	Vaccinium vitis-idaea	control	72 (7)
	(Lingonberry)	fertilized	23 (12)
Coastal			
FCE	Periphyton (algae)	Shark River Slough sites 1, 2, and 3,	
		Epiphyton substrate	9 (3)*
		Mat substrate	18 (2)
		Periphyton substrate	8 (2)
GCE	Plants	High Marsh site	4245 (238)
		Zone 1, Creek Bank	5984 (972)
PIE	*Spartina* spp. (Cordgrass)	*Spartina alterniflora*-dominated salt marsh at Goat Island, North Inlet, Georgetown, SC	547 (46)*
		Spartina alterniflora-dominated salt marsh at Law's Point, Rowley River, PIE, MA	560 (69)
		Spartina patens-dominated salt marsh at Law's Point, Rowley River, PIE, MA	1023 (87)
SBC	*Macrocystis pyrifera* (Kelp)	Arroyo Burro Reef, Santa Barbara Channel	185 (123)
		Arroyo Quemado Reef, Santa Barbara Channel	508 (90)
		Mohawk Reef, Santa Barbara Channel	530 (134)
VCR	Plants	Randomly selected, destructively sampled, non-treated plots at	
		Frank Day Well Location R2, Hog Island	112 (15)
		Frank Day Well Location R3, Hog Island	141 (27)
		Frank Day Well Location R4, Hog Island	139 (16)
Eastern forests			
HBR	Plants (kg/625 m^2)	Vegetation zone 1 at watershed 6	110 (15)
		Vegetation zone 4 at watershed 6	258 (29)
		Vegetation zone 5 at watershed 6	338 (37)
		Vegetation zones 2 and 3 at watershed 6	172 (20)
NTL	Aquatic plants	Trout Lake	39 (5)

Appendix 19. Average (standard error) biomass of primary producers (plants, algae) for sites with data—*Continued*

Site code	Taxon	Station	Biomass[1]	
Temperate grasslands and savannas				
CDR	Plants	Old Fields 24, 4, 41, 28	118	(7)
		Old Fields 72, 35, 45, 5	130	(8)
		Old Fields 77, 70, 26, 53	134	(9)
SPR	Forbs	Watershed 1	76	(7)
	Grass	Watershed 1	172	(17)
Western forests				
AND	Tree boles (kg/m^2)	Reference Stand 2	62	(6)
		Reference Stand 29	106	(3)

[1] The unit is g/m^2 if not specified.

* Linear regression of the variable against time is significant ($p < 0.05$) and the trend appears linear.

Appendix 20. Average (standard error) plant species richness for sites with data

(Multiple stations are given if possible. Sites are grouped by ecosystem type. See Appendix 28 for length of record for each station.)

Site code	Station	Richness[1]	Sampling area
Aridlands			
JRN	Creosote Study Sites	4(0.4)	1 m^2
		23(1.8)	49 m^2
	Grassland Study Sites	5(0.6)	1 m^2
		35(2.1)	49 m^2
	Mesquite Study Sites	3(0.3)	1 m^2
		17(1.5)	49 m^2
	Playa Study Sites	3(0.2)	1 m^2
		11(0.7)	49 m^2
	Tarbush Study Sites	4(0.2)	1 m^2
		21(1.6)	49 m^2
SEV	Blue Grama Study Site	10(0.8)	1 m^2
		53(2.6)	40 m^2
	Five-Points Grass Study Site	7(0.6)	1 m^2
		32(2.5)	40 m^2
	Five-Points *Larrea* Study Site	6(0.5)	1 m^2
		32(2.2)	40 m^2
SRE	Burned treatment: pasture 21	7(0.8)	9.3 m^2
	Control treatment: pastures 8 and 22	9(1.1)	9.3 m^2
	Pastures that were grazed and burned: pastures 2N and 6A	7(0.3)	9.3 m^2
	Pastures where the existing mesquite were killed and the pastures were grazed:pastures 3, 5N, 5S, 6B and 12B	8(0.5)	9.3 m^2
	Pastures where the mesquite were killed and the pastures were burned: pasture 2S	6(0.5)	9.3 m^2
WGE	Grass and scattered shrub vegetation zone	10(1.6)	30.5 m^2
	Grass vegetation zone	9(0.9)	30.5 m^2
	Shrubs and sparse grass vegetation zone	9(0.9)	30.5 m^2
	Shrubs with grass vegetation zone	9(0.6)	30.5 m^2
Eastern forests			
NTL	Site 31, Channel Mouth Island	5(0.8)	1.25 m^2
	Site 50, Southwest Bay of South Trout Lake	12(1.2)	1.25 m^2
	Site 56, Mouth of Mann Creek	11(1.1)	1.25 m^2
	Site 7, Rocky Reef Bay	3(0.6)	1.25 m^2
	Trout Lake	15(1.2)	5 m^2

Appendix 20. Average (standard error) plant species richness for sites with data—*Continued*

Site code	Station	Richness[1]	Sampling area
Temperate grasslands and savannas			
CDR	Old Fields 24, 4, 41, 28	5(0.2)	0.3 m^2
		17(0.5)	1.2 m^2
	Old Fields 72, 35, 45, 5	5(0.1)	0.3 m^2
		17(0.4)	1.2 m^2
	Old Fields 77, 70, 26, 53	5(0.1)	0.3 m^2
		21(0.6)	1.2 m^2
KBS	Treatment 7, native successional treatment, abandoned after spring plowing in 1989	11(0.5)	1 m^2
	Treatment 8, never plowed, 200 meters (m) south of the others, that serves as an historical control for soil organic matter studies	8(0.6)	1 m^2
	Treatment SF, old field successional community, never tilled	11(0.5)	1 m^2
Western forests			
AND	Watershed 1	119(3.6)	250 m^2
	Watershed 3	73(3.3)	250 m^2

[1] Unit is number of species per sampling area.

Appendix 21. Average (standard error) animal abundance for sites with data

(Multiple stations are given if possible. Sites are grouped by ecosystem type. See Appendix 28 for length of record for each station.)

Site code	Taxon	Station	Abundance		Unit
Aridlands					
JRN	Leporidae	Rabbit survey route in creosote vegetation zone	6	(1.1)*	#/10 km road
		Rabbit survey route in grassland vegetation zone	43	(5.6)*	#/10 km road
	Rodentia	Rodent trapping web in creosote vegetation zone	41	(4.7)	#/3.14 ha trapping web
		Rodent trapping web in grassland vegetation zone	43	(6.6)	#/3.14 ha trapping web
SEV	Rodentia	Five-Points Grass Study Site	26	(3.3)	#/trapping web
		Five-Points *Larrea* Study Site	47	(6.2)	#/trapping web
Coastal					
GCE	Orthoptera	Study Site 1, Eulonia, GA	2	(0.5)	#/20 m^2
		Study Site 3, North Sapelo, Sapelo Island, GA	1	(0.2)	#/20 m^2
		Study Site 6, Dean Creek, Sapelo Island, GA	4	(1.3)	#/20 m^2
MCR	Fish	MRB Lagoon research site	71	(17.1)*	#/m^3 coral
PAL	*Pygoscelis adeliae*	Palmer Station	8936	(780.4)	# breeding pairs
	P. antarcticus	Palmer Station	202	(16.3)*	# breeding pairs
PAL	*P. papua*	Palmer Station	491	(125.5)	# breeding pairs
VCR	Muridae	Hog Island Rodent Trapping Transect 1	6	(0.7)	#/trapping transect
		Hog Island Rodent Trapping Transect 4	3	(0.2)	#/trapping transect
		Hog Island Rodent Trapping Transect 5	3	(0.3)*	#/trapping transect
Eastern forests					
HBR	Aves	10-hectare bird count plot	123	(7.2)*	#/10 ha
	Lepidoptera	on *Acer saccharum*	18	(2.2)	#/4000 leaves
		on *Fagus grandifolia*	12	(2.0)	#/4000 leaves
LUQ	Aves	El Verde	3	(0.2)	# counted outside a 25 m -radius circle
			4	(0.1)*	# counted inside a 25 m -radius circle
	Caridea	El Verde Study Area, Pool 0, Quebrada Prieta	56	(3.5)*	#/pool
		Pool 15 in Quebrada Prieta (upstream pool)	70	(7.5)*	#/pool
		Pool 8 in Quebrada Prieta	46	(6.9)	#/pool

Appendix 21. Average (standard error) animal abundance for sites with data—*Continued*

Site code	Taxon	Station	Abundance		Unit
	Eleutherodactylus coqui	El Verde New Plot	19	(3.3)	#/400 m^2
		El Verde Old Plot	22	(3.1)	#/400 m^2
	Gastropoda	Luquillo Forest Dynamics Plot at El Verde	993	(173.0)	#/1130 m^2
NTL	Orconectes	Big Muskellunge Lake	21	(5.6)	# caught/unit effort
		Lake Mendota	0.003	(0.002)	# caught/unit effort
		Sparkling Lake	7	(0.9)	# caught/unit effort
		Trout Lake	59	(13.9)	# caught/unit effort
	Fish	Crystal Lake	510	(73.9)*	# caught/unit effort
		Sparkling Lake	265	(26.4)*	# caught/unit effort
		Trout Lake	646	(61.4)*	# caught/unit effort
Temperate grasslands and savannas					
CDR	Orthoptera	Cedar Creek	149	(23.3)	#/200 sweeps of an insect net
KBS	Neoptera	Treatment 1, standard levels of chemical inputs, conventional chisel plowed tillage	77	(12.2)	# adults/yellow sticky trap
		Treatment 2, standard levels of chemical inputs, no tillage	73	(11.8)	# adults/yellow sticky trap
		Treatment 3, organic-based low chemical input (banded herbicide, starter N), winter leguminous crop, annual tillage and post-planting cultivation	62	(10.4)	# adults/yellow sticky trap
		Treatment 4, certified organic, no chemical inputs, annual tillage, rotary-hoed to control weeds	66	(10.2)	# adults/yellow sticky trap
		Treatment 5, poplar trees (fallow 2008), planted on a 10-year rotation cycle	69	(10.4)	# adults/yellow sticky trap
		Treatment 6, continuous alfalfa (wheat 2008)	76	(10.7)	# adults/yellow sticky trap
		Treatment 7, native successional treatment, abandoned after spring plowing in 1989	88	(11.8)	# adults/yellow sticky trap
		Treatment 7, native successional treatment, abandoned after spring plowing in 1989	88	(11.8)	# adults/yellow sticky trap

Appendix 21. Average (standard error) animal abundance for sites with data—*Continued*

Site code	Taxon	Station	Abundance		Unit
KNZ	Mammalia	Watershed 001d	8	(1.1)	#/transect line/4-day trapping season
		Watershed 004b	12	(1.3)	#/transect line/4-day trapping season
	Orthoptera	Watershed 001d	346	(54.3)*	#/200 sweeps of an insect net
		Watershed 004b	374	(114.8)*	#/200 sweeps of an insect net
		Watershed 020b	126	(25.2)	#/200 sweeps of an insect net
SGS	Aves	USGS Bird Breeding Survey area 17901, Rockport, CO	20	(1.7)	#/sighting effort
		USGS Breeding Bird Survey Route 17305, Nunn, CO	32	(0.9)	#/sighting effort
Urban					
CAP	Araneae (spiders)	Agricultural study sites	0.4	(0.1)	#/pitfall trap
		Desert study sites	0.2	(0.03)	#/pitfall trap
		Urban study sites	0.4	(0.1)	#/pitfall trap
	Orthoptera	Agricultural study sites	0.4	(0.2)	#/pitfall trap
		Desert study sites	0.2	(0.05)	#/pitfall trap
		Urban study sites	1	(0.1)	#/pitfall trap
Western forests					
AND	*Oncorhynchus clarkii*	Clearcut section of Mack Creek	108	(6.1)	#/50 m reach of stream
		Old growth section of Mack Creek	91	(5.7)	#/50 m reach of stream

* indicates that the linear regression of the variable against time is significant ($p < 0.05$) and the trend appears linear.

Appendix 22. Average (standard error) animal species richness for sites with data

(Multiple stations are given if possible. Sites are grouped by ecosystem type. See Appendix 28 for length of record for each station.)

Site code	Taxon	Station	Richness[1]	Sampling area/effort
Coastal				
FCE	Osteichthyes	Shark Slough	12 (0.5)	Unknown
		Taylor Slough	10 (0.7)	Unknown
MCR	Fish	North Shore region (7 research sites)	67 (2.0)*	Unknown
Eastern forests				
HBR	Aves	10-ha bird count plot	22 (0.5)*	10 ha
NTL	Fish	Crystal Lake	8 (0.3)*	Unit effort
		Sparkling Lake	14 (0.4)	Unit effort
		Trout Lake	23 (0.4)	Unit effort
Temperate grasslands and savannas				
CDR	Orthoptera	Cedar Creek	10 (0.5)*	200 sweeps of an insect net
KNZ	Orthoptera	Watershed 001d	11 (1.2)	200 sweeps of an insect net
		Watershed 004b	11 (1.2)	200 sweeps of an insect net
		Watershed 020b	13 (1.1)	200 sweeps of an insect net
SGS	Aves	USGS Bird Breeding Survey area 17901, Rockport, CO	22 (0.6)	Sighting effort
		USGS Breeding Bird Survey Route 17305, Nunn, CO	32 (0.9)	Sighting effort

[1] Unit is number of species per sampling area or effort.
* Linear regression of the variable against time is significant ($p < 0.05$) and the trend appears linear.

Appendix 23. Regression coefficients and R^2 values for plant and animal variables for which linear regression of each variable against time is significant ($p < 0.05$) and the trend appears linear

(Sites are grouped by ecosystem type. See Appendix 28 for length of record for each station.)

Site code	Variable	Station	Slope	Y-intercept[1]	R^2
Alpine and arctic					
ARC	Aboveground net primary production	Nitrogen-fertilized ANPP plots	9.5	218.1	0.9
NWT	Aboveground net primary production	Dry meadow plots at Saddle site	-6.0	251.6	0.4
		Moist meadow plots at Saddle site	-3.8	238.4	0.4
		Wet meadow plots at Saddle site	5.0	131.4	0.6
Aridlands					
JRN	Aboveground net primary production	Grassland Plots	8.3	46.6	0.4
		Mesquite Plots	10.1	12.0	0.4
	Animal abundance, Leporidae	Rabbit survey route in creosote vegetation zone	-0.7	11.2	0.5
		Rabbit survey route in grassland vegetation zone	-3.7	69.2	0.5
SEV	Aboveground net primary production	Five-Points Grass Study Site	18.7	-10.5	0.7
Coastal					
CCE	Chlorophyll a	Ohman Region: subset of CalCOFI stations inshore and nearshore in the Southern California Bight region; CalCOFI lines 80-93, stations from shore offshore to station 70	0.02	0.6	0.3
FCE	Biomass, periphyton	Shark River Slough sites 1, 2, and 3, Epiphyton substrate	2.7	-1.7	0.6
MCR	Animal abundance, fish	MRB Lagoon research site	-17.5	158.9	0.9
	Animal species richness, fish	North Shore region (7 research sites)	1.6	58.8	0.5
PAL	Animal abundance, *Pygoscelis antarcticus*	Palmer Station	6.7	61.2	0.6
PIE	Aboveground net primary production	Spartina alterniflora-dominated salt marsh at Goat Island, North Inlet, Georgetown, SC	26.1	625.5	0.4
	Plant biomass	Spartina alterniflora-dominated salt marsh at Goat Island, North Inlet, Georgetown, SC	15.4	371.9	0.3
VCR	Animal abundance, Muridae	Hog Island Rodent Trapping Transect 5	-0.2	5.0	0.5

Appendix 23. Regression coefficients and R^2 values for plant and animal variables for which linear regression of each variable against time is significant ($p < 0.05$) and the trend appears linear—*Continued*

Site code	Variable	Station	Slope	Y-intercept[1]	R^2
Eastern forests					
HBR	Aboveground net primary production	Unknown	7.4	663.5	0.8
	Animal abundance, Aves	10-hectare bird count plot	-3.5	188.6	0.7
	Animal species richness, Aves	10-hectare bird count plot	-0.2	26.2	0.5
LUQ	Animal abundance, Aves	El Verde	-0.05	4.7	0.3
	Animal abundance, Caridea	El Verde Study Area, Pool 0, Quebrada Prieta	-1.1	68.9	0.2
		Pool 15 in Quebrada Prieta (upstream pool)	3.8	27.8	0.5
NTL	Animal abundance, fish	Crystal Lake	30.6	67.0	0.4
		Sparkling Lake	11.1	103.9	0.4
		Trout Lake	23.6	303.6	0.4
	Animal species richness, fish	Crystal Lake	0.1	6.9	0.1
Temperate grasslands and savannas					
CDR	Aboveground net primary production	Unknown	11.1	177.4	0.4
	Animal species richness, Orthoptera	Cedar Creek	-0.3	12.4	0.4
KBS	Aboveground net primary production	Treatment 7, native successional treatment, abandoned after spring plowing in 1989	21.9	314.8	0.5
		Treatment SF, old field successional community, never tilled	-9.9	275.4	0.4
KNZ	Animal abundance, Orthoptera	Watershed 001d	-17.5	554.5	0.3
		Watershed 004b	-32.1	756.0	0.2
SGS	Aboveground net primary production	ESA Control 1	-2.9	128.1	0.3
		Owl Creek, coarse texture soil	-4.6	144.8	0.3
Western forests					
AND	Animal abundance, fish	Old growth section of Mack Creek	2.4	67.1	0.3
CHE	Diameter at breast height, *Pseudotsuga menziesii* (Douglas fir)	HSGY Study Plots	1.0	50.7	1.0

[1] Y-intercept was calculated for the first year of a dataset, which contains records of one variable over time for one site.

Appendix 24. Lead principal investigators (PI) with information managers (IM) and administrative program of the LTER programs

Site code	Title	Name[1]	Affiliation[2]	Administrative program
AND	PI	Barbara Bond	Oregon State University	Oregon State University
	IM	Donald Henshaw	USFS Pacific Northwest Research Station	
ARC	PI	John E. Hobbie	Ecosystems Center,	Marine Biological Laboratory
	IM	James Laundre	Marine Biological Laboratory	
BES	PI	Steward T. A. Pickett	Cary Institute of Ecosystem Studies	Cary Institute of Ecosystem Studies
	IM	Jonathan Walsh		
BNZ	PI	F. Stuart Chapin	University of Alaska, Fairbanks	University of Alaska, Fairbanks
	IM	Jason Downing (C)		
	IM	Brian Riordan (P)		
CAP	PI	Nancy B. Grimm	Arizona State University	Arizona State University
	IM	Philip Tarrant		
		Corinna Gries		
CCE	PI	Mark D. Ohman	Scripps Institution of Oceanography	University of California at San Diego
	IM	Karen Baker	University of California at San Diego	
CDR	PI	G. David Tilman	University of Minnesota	University of Minnesota
	IM	Dan Bahauddin (C)		
		Stephanie Lyon (P)		
CWT	PI	Ted L. Gragson	University of Georgia	University of Georgia
	IM	John Chamblee (C)		
		Barrie Collins (P)		
FCE	PI	Evelyn E. Gaiser (C)	Florida International University	Florida International University
		Dan Childers (P)		
	IM	Linda Powell		

Appendix 24. Lead principal investigators (PI) with information managers (IM) and administrative program of the LTER programs—*Continued*

Site code	Title	Name[1]	Affiliation[2]	Administrative program
GCE	PI	Merryl Alber (C)	University of Georgia	University of Georgia
		Steve Pennings (P)	University of Houston	
	IM	Wade Sheldon	University of Georgia	
HBR	PI	Charles T. Driscoll	Syracuse University	Cornell University
	IM	John Campbell	USFS Northern Research Station	
HFR	PI	David R. Foster	Harvard University	Harvard University
	IM	Emery Boose		
JRN	PI	Debra P. C. Peters	USDA ARS Jornada Experimental Range	New Mexico State University
	IM	Ken Ramsey	New Mexico State University	
KBS	PI	G. Philip Robertson	Michigan State University	Michigan State University
	IM	Sven Bohm		
KNZ	PI	John M. Blair	Kansas State University	Kansas State University
	IM	Adam Skibbe (C)		
		Jincheng Gao (P)		
LUQ	PI	Nicholas V. L. Brokaw	University of Puerto Rico, Rio Piedras	University of Puerto Rico, Rio Piedras
	IM	Eda Melendez-Colom		
MCM	PI	Diane McKnight (C)	University of Colorado	Ohio State University
		William B. Lyons (P)	Ohio State University	
		Andrew Fountain (P)	Portland State University	
	IM	Susan A. Welch (C)	Ohio State University	
	IM	Chris Gardner (P)	Ohio State University	

Appendix 24. Lead principal investigators (PI) with information managers (IM) and administrative program of the LTER programs—*Continued*

Site code	Title	Name[1]	Affiliation[2]	Administrative program
MCR	PI	Russell J. Schmitt	University of California at Santa Barbara	University of California at Santa Barbara
	IM	Mary Gastil-Buhl (C)		
		Sabine Grabner (P)		
NTL	PI	Emily Stanley (C)	University of Wisconsin, Madison	University of Wisconsin, Madison
		Stephen R. Carpenter (P)		
	IM	Corinna Gries (C)		
		David Balsiger (P)		
		Barbara Benson (P)		
NWT	PI	Mark W. Williams	University of Colorado	University of Colorado
	IM	Hope Humphries (C)		
		Todd Ackerman (P)		
PAL	PI	Hugh W. Ducklow	Ecosystems Center, Marine Biological Laboratory	Marine Biological Laboratory
	IM	Karen Baker	University of California at San Diego	
PIE	PI	Anne Giblin (C)	Ecosystems Center, Marine Biological Laboratory	Marine Biological Laboratory
		Charles S. Hopkinson (P)		
	IM	Hap Garritt		
SBC	PI	Daniel C. Reed	University of California at Santa Barbara	University of California at Santa Barbara
	IM	Margaret O'Brien		
SEV	PI	Scott L. Collins (C)	University of New Mexico	University of New Mexico
		Jim Gosz (P)		
	IM	Kristin Vanderbilt		

Appendix 24. Lead principal investigators (PI) with information managers (IM) and administrative program of the LTER programs—*Continued*

Site code	Title	Name[1]	Affiliation[2]	Administrative program
SGS	PI	John Moore (C)	Colorado State University	Colorado State University
		Michael Antolin (P)		
		Eugene F. Kelly (P)		
	IM	Nicole Kaplan		
VCR	PI	Karen J. McGlathery	University of Virginia	University of Virginia
	IM	John Porter		

[1] C = Current PI or IM; P = Previous PI or IM.

[2] Affiliation when active in EcoTrends; may not represent current affiliation.

Appendix 25. Researchers involved in the EcoTrends project at non-LTER sites.

Site code	Title	Name	Affiliation[1, 2]
BEN	Project Leader	David Loftis	USFS Southern Research Station
	Lead Forestry Technician	Tracy Roof	
BLA	Vegetation Dynamics Team Leader	Martin Ritchie	USFS Pacific Southwest Research Station
	Forestry Technician	Brian Wing	
CHE	Wildlife Biologist/Research Natural Areas Coordinator	Todd Wilson	USFS Pacific Northwest Research Station
	Forester (retired)	Sarah Greene	
	Senior Faculty Research Assistant (former)	Howard Bruner	
CRO	Supervisory Ecologist and Project Leader	Jim Guldin	USFS Southern Research Station
CSP	Project Leader	Thomas Lisle	USFS Pacific Southwest Research Station Redwood Sciences Laboratory
	Mathematical Statistician (retired)	Jack Lewis	
EOA	Research Leader	Tony Svejcar	USDA ARS Eastern Oregon Agricultural Research Center
	Range Technician	Clare Pouslon	
FER	Supervisory Soil Scientist	Mary Beth Adams	USFS Northern Research Station
	Information Technology Specialist	Frederica Wood	
FRA	Research Hydrologist	Kelly Elder	USFS Rocky Mountain Research Station
FTK	Research Leader	Mark Petersen	USDA ARS Fort Keogh Livestock and Range Research Laboratory
	Research Leader (retired)	Rod Heitschmidt	
	Rangeland Scientist	Jennifer Muscha	
GLA	Plant physiologist	Bob Musselman	USFS Rocky Mountain Research Station
	Air and Water Quality Specialist	John Korfmacher	

Appendix 25. Researchers involved in the EcoTrends project at non-LTER sites—*Continued*

Site code	Title	Name	Affiliation[1, 2]
GRL	Research Leader Laboratory Director (retired)	Jean Steiner Herman Mayeux	USDA ARS Grazinglands Research Laboratory
GSW	Supervisory Ecologist Agricultural Engineer	Wayne Polley Daren Harmel	USDA ARS Grassland, Soil and Water Research Laboratory
HAR	Research Geneticist	James Roberds	USFS Southern Research Station
LVW	Senior Research Scientist	Jill Baron	USGS Fort Collins Science Center
MAR	Hydrologic Technician	Carrie Dorrance	USFS Northern Research Station
PRI	Forester Research Silviculturalist	Robert Denner Russell T. Graham	USFS Rocky Mountain Research Station
RCE	Research Plant Physiologist Research Hydraulic Engineer	Stuart Hardegree Gerald Flerchinger	USDA ARS Northwest Watershed Research Center
SAN	Project Leader Research Hydrologist	Carl Trettin Devendra M. Amatya	USFS Center for Forested Wetlands Research
SPR	Animal Scientist, Research Leader Research Leader (retired) Range Scientist (retired)	Stacey Gunter Phil Sims Robert Gillen	USDA ARS Southern Plains Range Research Station
TAL	Research Hydrologist	Dan Marion	USFS Center for Bottomland Hardwoods Research
WBW	Aquatic Ecologist	Patrick Mulholland	USDOE Oak Ridge National Laboratory
WGE	Research Leader Hydrologist	Susan Moran Timothy Keefer	USDA ARS Southwest Watershed Research

Appendix 25. Researchers involved in the EcoTrends project at non-LTER sites—*Continued*

Site code	Title	Name	Affiliation[1, 2]
SRE	Professor of Range Management	Mitch McClaren	University of Arizona
WIN	Wildlife Biologist/Research Natural Areas Coordinator	Todd Wilson	USFS Pacific Northwest Research Station
	Forester (retired)	Sarah Greene	
	Senior Faculty Research Assistant (former)	Howard Bruner	

[1] Agency abbreviations:
USDA ARS: U.S. Department of Agriculture, Agricultural Research Service
USFS: U.S. Department of Agriculture, Forest Service
USGS: U.S. Geological Survey
USDOE: U.S. Department of Energy

[2] Affiliation when active in EcoTrends; may not represent current affiliation.

Appendix 26. Stations and length of record for each climate variable by site

(Sites are grouped by ecosystem type.)

Site code	Variable	Station	Start	End
Alpine and arctic				
ARC	Air temperature	Toolik Lake Field Station	1989	2005
	Precipitation		1989	2005
	Ice duration	Toolik Lake	1988	2005
	Water clarity		1989	2004
	Water temperature		1975	2004
	Streamflow	Kuparuk River	1983	2004
GLA	Air temperature	Glacier Lakes Ecosystem Experiments Site	1989	2005
	Precipitation		1995	2005
LVW	Air temperature	USGS Biological Resources Division and Water Resources Division meteorological stations	1984	2006
	Precipitation	NADP Station CO98, Rocky Mountain National Park, Loch Vale, CO	1984	2006
	Streamflow	Loch Outlet	1984	2004
	Water temperature		1992	2006
MCM	Air temperature	Lake Hoare	1988	2007
	Precipitation	Lake Bonney	1995	2006
	Streamflow	Onyx River at Vanda	1969	2004
	Water temperature	Von Guerard Stream at F6	1990	2005
NWT	Air temperature	C-1 Meteorological Station	1953	2006
	Precipitation		1965	2006
	Ice duration	Green Lake 4	1982	2006
	Streamflow		1982	2001
Aridlands				
EOA	Air temperature	NWS COOP #358029, Squaw Butte Experimental Station, OR	1937	2008
	Precipitation		1937	2008
JRN	Air temperature	NWS COOP #294426, Jornada Experimental Range, NM	1916	2008
	Precipitation		1919	2008
RCE	Air temperature	NWS COOP #107648, Reynolds, ID	1962	2007
	Precipitation		1962	2007
	Streamflow	036x68 streamflow station	1963	1995
SEV	Air temperature	NWS COOP #298387, Socorro, NM	1893	2008
	Precipitation		1899	2008
SRE	Air temperature	NWS COOP #027593, Santa Rita Experimental Range, AZ	1951	2004
	Precipitation		1951	2004
WGE	Air temperature	NWS COOP #028619 Tombstone, AZ	1898	2007
	Precipitation		1898	2007
	Streamflow	Flume 1	1958	2008

Appendix 26. Stations and length of record for each climate variable by site—*Continued*

Site code	Variable	Station	Start	End
Coastal				
CCE	Air temperature	Lindbergh Field Airport, San Diego, CA	1927	2008
	Precipitation		1927	2008
	Sea level	NOAA Station 9410170, San Diego, CA	1906	2008
	Water clarity	Inshore Area at CCE	1969	2007
	Water temperature	Scripps Institution of Oceanography Pier	1917	2006
FCE	Air temperature	Royal Palm Ranger Station	1950	2008
	Precipitation		1950	2008
	Sea level	NOAA Station 8724580, Key West, FL	1913	2008
	Streamflow	Tamiami Canal at S-12-A (USGS 254543080491101)	1964	2008
	Water clarity	Duck Key, Taylor Slough/Panhandle Site 9	2000	2004
	Water temperature	National Data Buoy Center Station LONF1, Long Key, FL	1993	2008
GCE	Air temperature	NWS COOP #091340, Brunswick, GA	1915	2008
	Precipitation		1918	2008
	Sea level	NOAA Station 8670870, Ft. Pulaski, GA	1936	2008
	Streamflow	Altamaha River at Doctor Town (USGS)	1932	2008
	Water temperature	Hudson Creek	2002	2008
MCR	Air temperature	MeteoFrance Afareaitu #2	1977	2007
	Precipitation		1977	2007
	Sea level	Papeete station, Moorea	1976	2008
PAL	Air temperature	Palmer Station	1975	2008
	Precipitation		1990	2008
	Ice duration	Palmer Basin	1979	2006
PIE	Air temperature	NWS COOP #193505, Haverhill, MA	1901	2008
	Precipitation		1901	2008
	Sea level	NOAA Station 8443970, Boston, MA	1921	2008
	Streamflow	Parker River at Byefield MA (USGS)	1945	2009
SBC	Air temperature	NWS COOP #047902, Mission Creek, Santa Barbara, CA	1895	2006
	Precipitation	Santa Barbara County Public Works Department Flood Control District Site at Ellison Hall Roof, UC Santa Barbara	1952	2007
	Sea level	NOAA Station 9410660, Los Angeles, CA	1924	2008
	Streamflow	USGS Station 11119500, Carpinteria Creek near Carpinteria CA	1941	2007
	Water temperature	Santa Barbara Manual Shore Station, Santa Barbara Harbor	1955	2004
VCR	Air temperature	NWS COOP #446475, Painter 2W, VA	1956	2007
	Precipitation		1956	2007
	Sea level	NOAA Station 8534720, Atlantic City, NJ	1912	2008
	Water clarity	Phillips Creek Mouth	1992	2008

Appendix 26. Stations and length of record for each climate variable by site—*Continued*

Site code	Variable	Station	Start	End
Eastern forests				
BEN	Air temperature	NWS COOP #310724, Bent Creek, NC	1949	2008
	Precipitation		1949	2004
	Streamflow	USGS Station 03448000, French Broad River at Bent Creek, NC	1935	1986
CRO	Air temperature	NWS COOP #031730, Crossett 7 S, Crossett, AR	1916	2008
	Precipitation		1916	2008
CWT	Air temperature	NWS COOP #312102, Coweeta Experimental Station, NC	1943	2008
	Precipitation		1944	2008
	Streamflow	Watershed 18 flume	1937	2007
FER	Air temperature	NWS COOP #466867, Parsons 1 NE, WV	1899	2006
	Precipitation		1905	2006
	Streamflow	Watershed 1 at Fernow	1952	2007
HAR	Air temperature	NWS COOP #227840, Saucier Experimental Forest, MS	1955	2004
	Precipitation		1955	2006
HBR	Air temperature	Weather Station Headquarters	1957	2007
	Ice duration	Mirror Lake	1968	2005
	Precipitation	Hubbard Brook Ecosystem Study Headquarters	1978	2008
	Streamflow	GS Watershed 6	1963	2007
HFR	Air temperature	Harvard Forest Meteorological Stations Shaler and Fisher (sequential at same site)	1964	2008
	Precipitation		1964	2008
LUQ	Air temperature	Bisley Tower	1996	2004
	Precipitation		1988	2004
	Sea level	NOAA Station 9755371, San Juan, PR	1963	2008
	Streamflow	Puente Roto gage	1987	2006
MAR	Air temperature	NWS COOP #213303, Grand Rapids Forest Lab, MN	1916	2007
	Precipitation		1916	2007
	Streamflow	Total runoff of South Unit Watershed S2 weir	1962	2006
NTL	Air temperature	NWS COOP #475516, Minocqua Dam, WI	1904	2008
	Precipitation		1904	2008
	Ice duration	Lake Mendota	1856	2008
	Streamflow	USGS Station 05427948, Pheasant Branch at Middleton, WI	1975	2007
	Water clarity	Sparkling Lake	1981	2007
	Water temperature		1982	2008
SAN	Air temperature (max and min)	NWS COOP #388922, Walterboro 1 SW, Walterboro, SC	1904	2008
	Air temperature (mean)	Conglomerate of data from Santee, ChARP, Lotti, Met5, Met25, and Witherbee weather stations	1946	2005
	Precipitation		1946	2007
	Streamflow	Control Watershed 80 flume	1990	1999

Appendix 26. Stations and length of record for each climate variable by site—*Continued*

Site code	Variable	Station	Start	End
TAL	Air temperature	NWS COOP #229079, University, MS	1902	2008
	Precipitation		1905	2008
WBW	Air temperature	NWS COOP #406750, Oak Ridge, TN	1949	2008
	Precipitation		1949	2008
	Streamflow	West Fork of Walker Branch Watershed	1982	2005
Temperate grasslands and savannas				
CDR	Air temperature	NWS COOP #211227, Cambridge 5ESE, MN	1893	2007
	Precipitation	Conglomerate of Ft. Snelling and Composite datasets	1837	2008
FTK	Air temperature	NWS COOP #245690, Miles City-Frank Wiley Field, MT	1938	2008
	Precipitation		1938	2008
GRL	Air temperature	NWS COOP #342818, El Reno 1 N, NV	1893	2006
	Precipitation		1893	2006
GSW	Air temperature	Riesel, TX	1940	2008
	Precipitation	Rain Gauge 75A	1938	2008
	Streamflow	Stream gage Y2	1940	2008
KBS	Air temperature	NWS COOP #203504, Gull Lake Biological Station, MI	1934	2008
	Precipitation		1931	2008
	Ice duration	Gull Lake, MI	1924	2006
	Streamflow	Kalamazoo River at Comstock, MI (USGS)	1931	2009
KNZ	Air temperature	NWS COOP #144972, Manhattan, KS	1899	2008
	Precipitation		1898	2008
	Streamflow	USGS Station 06879650, Kings Creek near Manhattan, KS	1980	2008
SGS	Air temperature	Central Plains Experimental Range (1944-1968) and Shortgrass Steppe 11 (1969-present) weather stations	1944	2008
	Precipitation		1944	2009
SPR	Air temperature	NWS COOP #349760, Woodward, OK	1909	1976
	Precipitation		1909	2007
Urban				
BES	Air temperature	NWS COOP #180465, Baltimore Washington International Airport, MD	1940	2008
	Precipitation		1940	2008
	Sea level	NOAA Station 8574680, Baltimore, MD	1903	2008
	Streamflow	Villanova	1957	2009
CAP	Air temperature	NWS COOP #021026, Buckeye AZ	1894	2002
	Precipitation		1894	2002
	Streamflow	USGS Station 09502000, Salt River below Stewart Mountain Dam, AZ	1941	2007

Appendix 26. Stations and length of record for each climate variable by site—*Continued*

Site code	Variable	Station	Start	End
Western forests				
AND	Air temperature	Climatic Station at Watershed 2	1958	2006
	Precipitation		1958	2006
	Streamflow	Watershed 2	1953	2008
	Water temperature	Lookout Creek upper thermograph site	1977	2006
BNZ	Air temperature	LTER1	1989	2009
	Streamflow	C3 Flume in the Caribou-Poker Creeks Research Watershed	1969	2007
CHE	Air temperature	NWS COOP #356366, Otis, OR	1950	2008
	Precipitation		1949	2008
CSP	Air temperature	NWS COOP #043161, Fort Bragg 5N, CA	1935	2008
	Precipitation		1913	2008
	Streamflow	South Fork Caspar Creek	1986	2004
	Water temperature	ARF Station	1989	2004
FRA	Air temperature	NWS COOP #053261, Georgetown, CO	1898	2006
	Precipitation		1909	2006
	Streamflow	Lower Fool Creek	1941	1984
PRI	Air temperature	NWS COOP #107386, Priest River Experimental Station, ID	1901	2008
	Precipitation		1901	2008
	Streamflow	USGS Station 12395000, Priest River near Priest River, ID	1950	2008
WIN	Air temperature	NWS COOP #459342, Wind River, WA and NWS COOP #451160, Carson Fish Hatchery, WA	1931	2009
	Precipitation		1931	2008

Appendix 27. Stations and length of record for each precipitation or surface water chemistry variable by site

(Sites grouped by ecosystem type.)

Site code	Variable[1]	Station	Start	End
Alpine and arctic				
ARC	PPT: concentration	Toolik Lake Field Station	1989	2003
	PPT: deposition: ammonium, nitrate		1988	2003
	Stream: ammonium	Kuparuk River	1990	2006
	Stream: nitrate		1990	2005
GLA	PPT: concentration, deposition	NADP Station WY00, Snowy Range, WY	1986	2008
LVW	PPT: concentration, deposition	NADP Station CO98, Rocky Mountain National Park, Loch Vale, CO	1984	2008
	Stream	Loch Outlet	1992	2006
MCM	Lake: ammonium, nitrate	East Lake Bonney	1993	2007
	Lake: calcium, chloride, sulfate		1993	2006
NWT	Lake: ammonium	Green Lake 4	1993	2006
	Lake: calcium, sulfate		1982	2006
	Lake: chloride, nitrate		1985	2006
	PPT: concentration, deposition	NADP Station CO02, Niwot Saddle	1984	2008
Aridlands				
JRN	PPT: concentration, deposition	LTER Weather Station	1984	2008
RCE	PPT: concentration, deposition	NADP Station ID11, Reynolds Creek, ID	1984	2008
WGE	PPT: concentration, deposition	NADP Station AZ98, Chiricahua, AZ	2000	2008
Coastal				
CCE	Coastal water: nitrate	Ohman Region: subset of CalCOFI stations inshore and nearshore in the Southern California Bight region; CalCOFI lines 80-93, stations from shore offshore to station 70	1984	2005
FCE	Coastal water: ammonium, nitrate	Taylor Slough/Panhandle Site 6a	2002	2007
	PPT: concentration, deposition	NADP Station FL11, Everglades National Park Research Center, FL	1982	2008
GCE	PPT: concentration, deposition	NADP Station GA33, Sapelo Island, GA	2004	2008

Appendix 27. Stations and length of record for each precipitation or surface water chemistry variable by site—*Continued*

Site code	Variable[1]	Station	Start	End
PAL	Coastal water: ammonium	Palmer Station B	1995	2006
	Coastal water: nitrate		1994	2007
PIE	PPT: concentration, deposition	NADP Station MA13, East, MA	1982	2008
	Stream: ammonium, nitrate	Ipswich Dam	1994	2003
SBC	Coastal water: ammonium	Arroyo Quemado Reef, Santa Barbara Channel	2002	2007
	Coastal water: nitrate		2001	2007
VCR	Coastal water: ammonium, nitrate	Phillips Creek Mouth	1992	2007
	PPT: concentration, deposition	Oyster, VA at LTER Lab in Shirley House, Rt 600 and GATR Tract	1990	2007
Eastern forests				
BEN	PPT: concentration, deposition	NADP Station NC45, Mt. Mitchell, NC	1985	2008
CRO	PPT: concentration, deposition	NADP Station AR02, Warren 2WSW	1983	2008
CWT	PPT: concentration, deposition	NADP Station NC25, Coweeta, NC	1979	2008
FER	PPT: concentration, deposition	NADP Station WV18, Parsons, WV	1979	2008
	Stream: calcium, nitrate, sulfate	Watershed 4	1980	2006
	Stream: chloride		1988	2006
HBR	PPT: concentration, deposition	NADP Station NH02, Hubbard Brook, NH	1979	2008
	Stream: ammonium	Watershed 6	1967	2005
	Stream: calcium		1964	2005
	Stream: chloride, nitrate, sulfate		1965	2005
HFR	PPT: concentration, deposition	NADP Station MA08, Quabbin Reservoir, MA	1985	2008
LUQ	PPT: concentration, deposition	NADP Station PR20, El Verde, PR	1986	2008
	Stream: except sulfate	Quebrada Bisley 3 Cuenca	1986	2007
	Stream: sulfate		1986	2002
MAR	PPT: concentration, deposition	NADP Station MN16, Marcell Experimental Forest, MN	1979	2008
NTL	Lake: ammonium, nitrate	Sparkling Lake	1984	2007
	Lake: calcium, chloride, sulfate		1982	2007
	PPT: concentration, deposition	NADP Station WI36, Trout Lake, WI	1980	2008
SAN	PPT: concentration, deposition	NADP Station SC06, Santee National Wildlife Refuge, SC	1985	2008
TAL	PPT: concentration, deposition	NADP Station MS30, Coffeeville, MS	1985	2008

Appendix 27. Stations and length of record for each precipitation or surface water chemistry variable by site—*Continued*

Site code	Variable[1]	Station	Start	End
WBW	PPT: concentration, deposition	NADP Station TN00, Walker Branch Watershed, TN	1981	2008
	Stream	West Fork of Walker Branch Watershed	1989	2005
Temperate grasslands and savannas				
CDR	PPT: concentration, deposition	NADP Station MN01, Cedar Creek, MN	1997	2008
GRL	PPT: concentration, deposition	NADP Station OK17, Kessler Farm Field Laboratory, OK	1984	2006
KBS	PPT: concentration, deposition	NADP Station MI26, Kellogg Biological Station, MI	1980	2008
	Stream	Augusta Creek	1998	2008
KNZ	PPT: concentration, deposition	NADP Station KS31, Konza Prairie, KS	1983	2008
	Stream: ammonium	N04D	1989	2004
	Stream: nitrate		1985	2004
SGS	PPT: concentration, deposition	NADP Station CO22, Pawnee, CO	1980	2008
Urban				
BES	PPT: Concentration	NADP Station MD13, Wye, MD	1984	2008
	PPT: deposition: calcium, chloride		1984	2008
	PPT: deposition: ammonium, nitrate, sulfate	CASTNET Station BEL116, Beltsville, MD	1989	2006
	Stream: chloride, nitrate, sulfate	USGS Station #01589180, Gwynns Falls at Glyndon, MD	1999	2008
CAP	PPT: concentration	Lost Dutchman State Park Deposition Site	1999	2007
	PPT: deposition: ammonium, chloride, nitrate		2000	2005
	PPT: deposition: sulfate		2000	2003
	Stream	Lower Salt River	1998	2008
Western forests				
AND	PPT: concentration except sulfate	NADP Station OR10, H. J. Andrews Experimental Forest, OR	1981	2008
	PPT: deposition except sulfate		1981	2008
	PPT: concentration, deposition: sulfate		1985	2008
	Stream: ammonium, calcium, nitrate	Watershed 2	1982	2006

Appendix 27. Stations and length of record for each precipitation or surface water chemistry variable by site—*Continued*

Site code	Variable[1]	Station	Start	End
AND	Stream: chloride		1990	2006
	Stream: sulfate		1991	2006
BLA	PPT: concentration, deposition	NADP Station CA96, Lassen Volcanic National Park Manzanita Lake	2000	2008
BNZ	PPT: concentration	NADP Station AK01, Poker Creek	1994	2008
	PPT: deposition except ammonium		1993	2008
CSP	PPT: concentration, deposition	NADP Station CA45, Hopland, CA	1980	2007
FRA	PPT: concentration, deposition	NADP Station CO02, Niwot Saddle	1984	2008
PRI	PPT: concentration, deposition	NADP Station ID02, Priest River Experimental Forest, ID	2003	2007

[1] Up to five variables were measured at each station: calcium, chloride, nitrogen (ammonium and nitrate), and sulfur (sulfate). When the elements are not specified, concentration or deposition of all five elements is given. When the elements are specified, concentration or deposition is given for the elements specified.

Appendix 28. Stations and length of record for each plant and animal variable by site, as grouped by ecosystem type

Site code	Variable	Station	Start	End
Alpine and arctic				
ARC	Aboveground net primary production	Control ANPP plots	1982	2000
		Nitrogen-fertilized ANPP plots	1983	2000
	Chlorophyll a	Fertilized reach of Kuparuk River	1983	2004
		Reference reach of Kuparuk River	1983	2004
		Toolik Lake	1985	2004
	Plant biomass			
	Betula nana (dwarf birch)	Tussock Tundra 1981 Plots, control	1982	2000
	Eriophorum vaginatum (tussock cottongrass)		1982	2000
	Ledum palustre (marsh Labrador tea)		1982	2000
	Vaccinium vitis-idaea (lingonberry)		1982	2000
	B. nana	Tussock Tundra 1981 Plots, fertilized	1983	2000
	E. vaginatum		1983	2000
	L. palustre		1983	2000
	V. vitis-idaea		1983	2000
MCM	Primary production, measured as carbon	East Lake Bonney	1989	2007
		West Lake Bonney	1992	2007
NWT	Aboveground net primary production	Dry meadow plots at Saddle Location	1982	1997
		Moist meadow plots at Saddle Location	1982	1997
		Wet meadow plots at Saddle Location	1982	1997
Aridlands				
JRN	Aboveground net primary production	Creosote Study Sites	1990	2008
	Plant species richness		1989	2008
	Aboveground net primary production	Grassland Study Sites	1990	2008
	Plant species richness		1989	2008
	Aboveground net primary production	Mesquite Study Sites	1990	2008
	Plant species richness		1989	2008
	Aboveground net primary production	Playa Study Sites	1990	2008
	Plant species richness		1989	2008
	Aboveground net primary production	Tarbush Study Sites	1990	2008
	Plant species richness		1989	2008

Appendix 28. Stations and length of record for each plant and animal variable by site, as grouped by ecosystem type—*Continued*

Site code	Variable	Station	Start	End
	Animal abundance, Leporidae	Rabbit survey route in creosote vegetation zone	1996	2008
		Rabbit survey route in grassland vegetation zone	1996	2008
	Animal abundance, Rodentia	Rodent trapping web in creosote vegetation zone	1995	2007
		Rodent trapping web in grassland vegetation zone	1995	2007
SEV	Aboveground net primary production	Blue Grama Study Site	2002	2008
	Plant species richness		2002	2008
	Aboveground net primary production	Five-Points Grass Study Site	1999	2008
	Animal abundance, Rodentia		1989	2008
	Plant species richness		1999	2008
	Aboveground net primary production	Five-Points Larrea Study Site	1999	2008
	Animal abundance, Rodentia		1989	2008
	Plant species richness		1999	2008
SRE	Plant species richness	Burned treatment: pasture 21	1972	2006
		Control treatment: pastures 8 and 22	1972	2006
		Pastures that were grazed and burned: pastures 2N and 6A	1972	2006
		Pastures where the existing mesquite were killed and were grazed: pastures 3, 5N, 5S, 6B and 12B	1972	2006
		Pastures where the mesquite were killed and were burned: pasture 2S	1972	2006
WGE	Plant species richness	Grass and scattered shrub vegetation zone	1967	2005
		Grass vegetation zone	1967	2007
		Shrubs and sparse grass vegetation zone	1967	2007
		Shrubs with grass vegetation zone	1967	2005
Coastal				
CCE	Chlorophyll a	Ohman Region: subset of CalCOFI stations inshore and nearshore in the Southern California Bight region; CalCOFI lines 80-93, stations from shore offshore to station 70	1984	2005
	Primary production (carbon)		1984	2005
FCE	Animal species richness, Osteichthyes	Shark Slough	1996	2005
		Taylor Slough	1996	2005
	Biomass, periphyton	Shark River Slough sites 1, 2, and 3, Epiphyton substrate	2001	2007

Appendix 28. Stations and length of record for each plant and animal variable by site, as grouped by ecosystem type—*Continued*

Site code	Variable	Station	Start	End
	Net primary production (carbon)		2001	2007
	Biomass, periphyton	Shark River Slough sites 1, 2, and 3, Mat substrate	2002	2007
	Net primary production (carbon)		2002	2007
	Biomass, periphyton	Shark River Slough sites 1, 2, and 3, Periphyton substrate	2002	2007
	Net primary production (carbon)		2002	2007
GCE	Animal abundance, Orthoptera	Study Site 1, Eulonia, GA	2000	2008
		Study Site 3, North Sapelo, Sapelo Island, GA	2000	2008
		Study Site 6, Dean Creek, Sapelo Island, GA	2000	2008
	Plant biomass	High Marsh site	2000	2007
		Zone 1, Creek Bank	2000	2007
MCR	Animal abundance, fish	MRB Lagoon research site	2000	2008
	Animal species richness, fish	North Shore region (7 research sites)	2000	2008
	Chlorophyll a	SeaWiFS data for Moorea Coral Reef Vicinity, area for chlorophyll and SST data	1998	2008
PAL	Animal abundance, *Pygoscelis adeliae*	Palmer Station	1975	2008
	Animal abundance, *P. antarcticus*		1976	2008
	Animal abundance, *P. papua*		1994	2008
	Primary production (carbon)		1991	2006
	Chlorophyll a	Palmer Station B	1991	2006
PIE	Aboveground net primary production	*Spartina alterniflora*-dominated salt marsh at Goat Island, North Inlet, Georgetown, SC	1985	2005
	Plant biomass		1984	2005
	Aboveground net primary production	*S. alterniflora*-dominated salt marsh at Law's Point, Rowley River, Plum Island Ecosystem, MA	1999	2005
	Plant biomass		1999	2005
	Aboveground net primary production	*S. patens*-dominated salt marsh at Law's Point, Rowley River, Plum Island Ecosystem, MA	2001	2005
	Plant biomass		2001	2005
SBC	Biomass, *Macrocystis pyrifera* (Kelp)	Arroyo Burro Reef, Santa Barbara Channel	2002	2008
		Arroyo Quemado Reef, Santa Barbara Channel	2002	2008
		Mohawk Reef, Santa Barbara Channel	2002	2008

Appendix 28. Stations and length of record for each plant and animal variable by site, as grouped by ecosystem type—*Continued*

Site code	Variable	Station	Start	End
VCR	Animal abundance, Muridae	Hog Island Rodent Trapping Transect 1	1989	2004
		Hog Island Rodent Trapping Transect 4	1989	2004
		Hog Island Rodent Trapping Transect 5	1989	2004
	Plant biomass	Randomly selected, destructively sampled, non-treated plots		
		at Frank Day Well Location R2, Hog Island	1993	2006
		at Frank Day Well Location R3, Hog Island	1993	2006
		at Frank Day Well Location R4, Hog Island	1993	2006
Eastern forests				
BEN	Diameter at breast height of trees	Mixed hardwood plots	1975	2000
		Yellow Poplar plots	1961	2001
CRO	Production of seeds, pine	Unknown	1980	2004
	Production volume, pine	Clearcut logging stands	1948	1996
		Diameter limit logging stands	1948	1996
		Heavy seedtree logging stands	1948	1996
		Selection logging stands	1948	1996
HAR	Diameter at breast height, *Pinus palustris* (longleaf pine)	North plantation	1960	2000
	Height, *P. palustris*		1960	2000
	Diameter at breast height, *P. palustris*	South plantation	1960	2000
	Height, *P. palustris*		1960	2000
HBR	Aboveground net primary production	Unknown	1987	1996
	Animal abundance, Aves	10-hectare bird count plot	1969	2004
	Animal species richness, Aves		1969	2004
	Animal abundance, Lepidoptera	on *Acer saccharum*	1986	1997
		on *Fagus grandifolia*	1986	1997
	Diameter at breast height of trees	Vegetation zone 1 at watershed 6	1965	2002
	Plant biomass		1965	2002
	Diameter at breast height of trees	Vegetation zones 2 and 3 at watershed 6	1965	2002
	Plant biomass		1965	2002
	Diameter at breast height of trees	Vegetation zone 4 at watershed 6	1965	2002
	Plant biomass		1965	2002

Appendix 28. Stations and length of record for each plant and animal variable by site, as grouped by ecosystem type—*Continued*

Site code	Variable	Station	Start	End
	Diameter at breast height of trees	Vegetation zone 5 at watershed 6	1965	2002
	Plant biomass		1965	2002
HFR	Aboveground net primary production of trees	Little Prospect Hill	2002	2006
	Diameter at breast height of trees	Lyford Blocks within the Prospect Hill Tract	1969	2001
LUQ	Animal abundance, Aves	El Verde	1989	2008
	Animal abundance, Caridea	El Verde Study Area, Pool 0, Quebrada Prieta	1988	2008
		Pool 15 in Quebrada Prieta (upstream pool)	1988	2008
		Pool 8 in Quebrada Prieta	1988	2008
	Animal abundance, *Eleutherodactylus coqui*	El Verde New Plot	1987	1997
		El Verde Old Plot	1987	1997
	Animal abundance, Gastropoda	Luquillo Forest Dynamics Plot at El Verde	1991	2007
NTL	Animal abundance, Orconectes	Big Muskellunge Lake	1981	2008
		Lake Mendota	1981	2008
		Sparkling Lake	1981	2008
	Animal abundance, fish		1981	2008
	Animal species richness, fish		1981	2008
	Animal abundance, Orconectes	Trout Lake	1981	2008
	Animal abundance, fish		1981	2008
	Animal species richness, fish		1981	2008
	Plant biomass	Trout Lake	1983	2008
	Plant species richness		1983	2008
	Animal abundance, fish	Crystal Lake	1981	2008
	Animal species richness, fish		1981	2008
	Plant species richness	Site 31, Channel Mouth Island	1983	2008
		Site 50, Southwest Bay of South Trout Lake	1983	2008
		Site 56, Mouth of Mann Creek	1983	2008
		Site 7, Rocky Reef Bay	1983	2008
	Primary production, hypsometrically weighted	Crystal Lake, epilimnion	1987	2007
		Sparkling Lake, epilimnion	1987	2007
		Trout Lake, epilimnion	1987	2007

Appendix 28. Stations and length of record for each plant and animal variable by site, as grouped by ecosystem type—*Continued*

Site code	Variable	Station	Start	End
Temperate grasslands and savannas				
CDR	Aboveground net primary production	Unknown	1982	1998
	Animal abundance, Orthoptera	Cedar Creek	1989	2004
	Animal species richness, Orthoptera		1989	2004
	Plant biomass	Old Fields 4, 24, 28, 41	1988	2003
	Plant species richness		1988	2006
	Plant biomass	Old Fields 5, 35, 45, 72	1988	2003
	Plant species richness		1988	2006
	Plant biomass	Old Fields 26, 53, 70, 77	1988	2003
	Plant species richness		1988	2006
FTK	Aboveground net primary production	Lysimeter 1	1993	2004
		Lysimeter 8	1993	2004
KBS	Aboveground net primary production	Treatment 7, native successional treatment, abandoned after spring plowing in 1989	1991	2008
	Plant species richness		1991	2008
	Animal abundance, Neoptera		1989	2008
	Aboveground net primary production	Treatment 8, never plowed, 200 meters (m) south of the others, that serves as an historical control for soil organic matter studies	1991	2008
	Plant species richness		1991	2008
	Aboveground net primary production	Treatment SF, old field successional community, never tilled	1993	2008
	Plant species richness		1993	2008
	Animal abundance, Neoptera	Treatment 1, standard levels of chemical inputs, conventional chisel plowed tillage	1989	2008
		Treatment 2, standard levels of chemical inputs, no tillage	1989	2008
		Treatment 3, organic-based low chemical input (banded herbicide,starter N), winter leguminous crop, annual tillage and post-planting cultivation	1989	2008
		Treatment 4, certified organic, no chemical inputs, annual tillage, rotary-hoed to control weeds	1989	2008
		Treatment 5, Poplar trees (fallow 2008), planted on a 10-year rotation cycle	1989	2008

Appendix 28. Stations and length of record for each plant and animal variable by site, as grouped by ecosystem type—*Continued*

Site code	Variable	Station	Start	End
KBS	Animal abundance, Neoptera	Treatment 6, Continuous alfalfa (wheat 2008)	1989	2008
KNZ	Aboveground net primary production	Watershed 020b, burned every 20 years, on deep Tully soils	1984	2005
		Watershed 020b, burned every 20 years, on shallow Florence soils	1984	2005
	Animal abundance, Mammalia	Watershed 001d	1981	1997
	Animal abundance, Orthoptera		1982	2004
	Animal species richness, Orthoptera		1982	2004
	Animal abundance, Mammalia	Watershed 004b	1981	1997
	Animal abundance, Orthoptera		1982	2004
	Animal species richness, Orthoptera		1982	2004
	Animal abundance, Orthoptera	Watershed 020b	1996	2004
	Animal species richness, Orthoptera		1996	2004
SGS	Aboveground net primary production	ESA Control 1	1983	2007
		Owl Creek, coarse texture soil	1991	2007
		Sec 25, fine texture soil	1991	2007
	Animal abundance, Aves	USGS Bird Breeding Survey area 17901, Rockport, CO	1995	2008
	Animal species richness, Aves		1994	2008
	Animal abundance, Aves	USGS Breeding Bird Survey Route 17305, Nunn, CO	1995	2008
	Animal species richness, Aves		1995	2008
SPR	Plant biomass, forbs	Watershed 1	1984	2005
	Plant biomass, grass		1984	2005
Urban				
CAP	Animal abundance, Araneae (spiders)	Agricultural study sites	1998	2004
	Animal abundance, Orthoptera		1998	2003
	Animal abundance, Araneae (spiders)	Desert study sites	1998	2004
	Animal abundance, Orthoptera		1998	2004
	Animal abundance, Araneae (spiders)	Urban study sites	1998	2004
	Animal abundance, Orthoptera		1998	2004

Appendix 28. Stations and length of record for each plant and animal variable by site, as grouped by ecosystem type—*Continued*

Site code	Variable	Station	Start	End
Western forests				
AND	Aboveground net primary production, tree boles	Reference Stand 2	1988	2005
	Plant biomass, tree boles		1988	2005
	Aboveground net primary production, tree boles	Reference Stand 29	1983	2001
	Plant biomass, tree boles		1988	2005
	Animal abundance, *Oncorhynchus clarkii*	Clearcut section of Mack Creek	1987	2007
		Old growth section of Mack Creek	1987	2007
	Plant species richness	Watershed 1	1962	2008
		Watershed 3	1962	2008
BNZ	Aboveground net primary production	Unknown	1991	1998
CHE	Diameter at breast height	HSGY Study Plots		
	Picea sitchensis (Sitka spruce)		1935	2003
	Pseudotsuga menziesii (Douglas fir)		1935	2003
	Tsuga heterophylla (Western hemlock)		1935	2003

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