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).

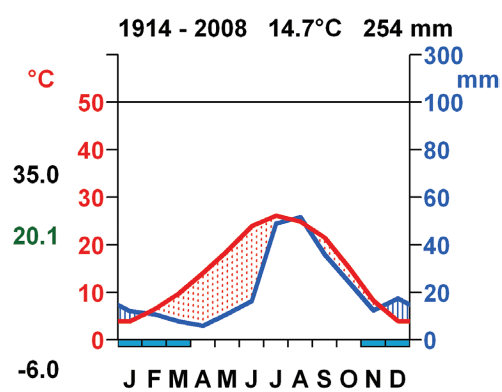


Figure 11-1. Example of a Walter-Lieth climate diagram for one site, Jornada (JRN). Mean monthly temperature in degrees Celsius (left axis, red) is plotted with precipitation in millimeters (right axis, blue) for each month in the year (bottom axis, J-D = January-December). Areas shaded in speckled red 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.

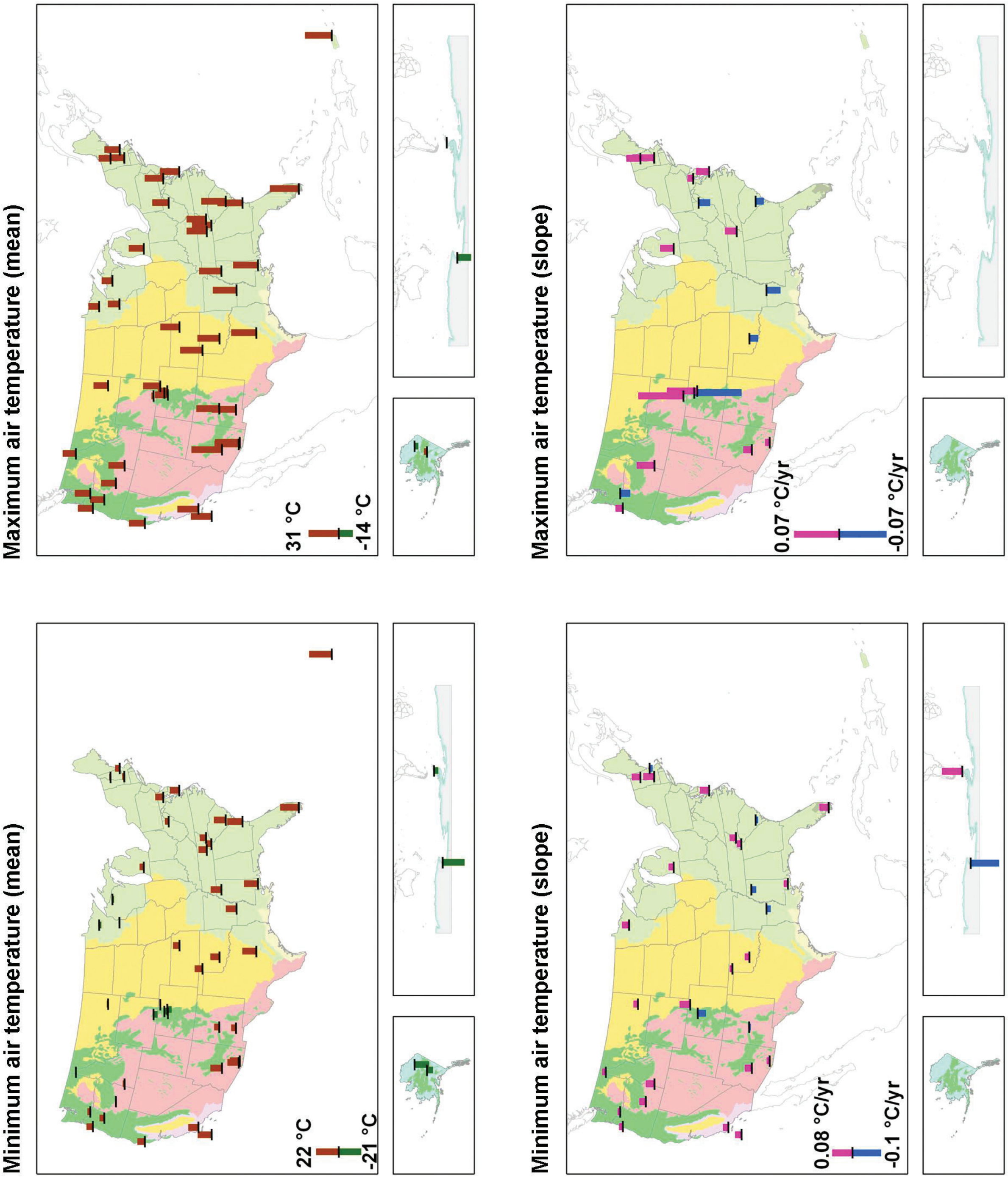


Figure 11-2. Top panels: continental patterns of long-term average annual minimum and maximum air temperature (°C) for all sites. (Positive values are red; negative values are green.) Bottom panels: slopes of significant regression lines ($p < 0.05$). (Positive values are pink; negative values are blue.)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

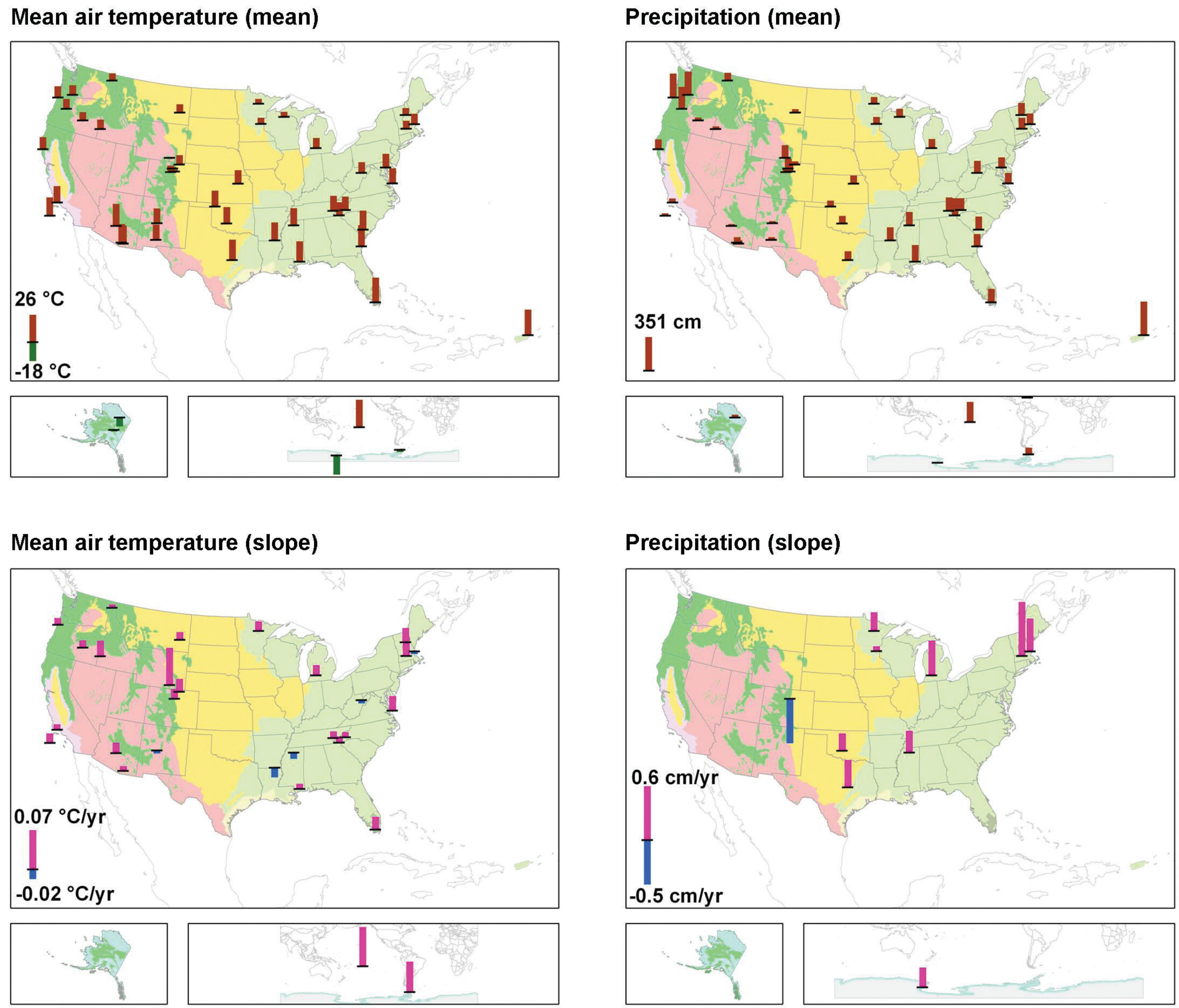


Figure 11-3. Top panels: continental patterns of long-term average annual mean air temperature (°C) and annual precipitation (cm) for all sites. (Positive values are red; negative values are green). Bottom panels: slopes of significant regression lines ($p < 0.05$). (Positive values are pink; negative 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.

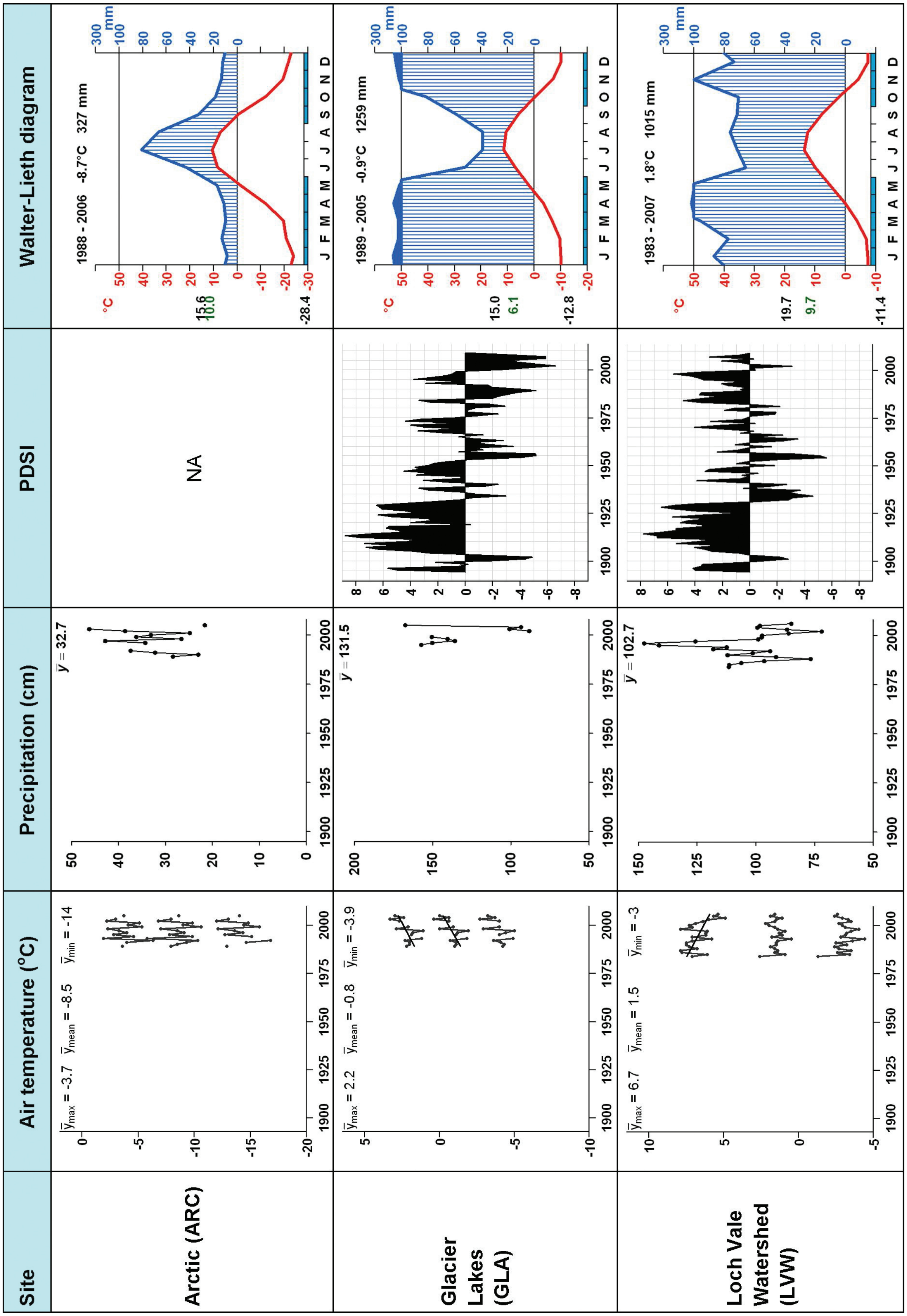


Figure 11-4 (Alpine and Arctic sites) continued next page.

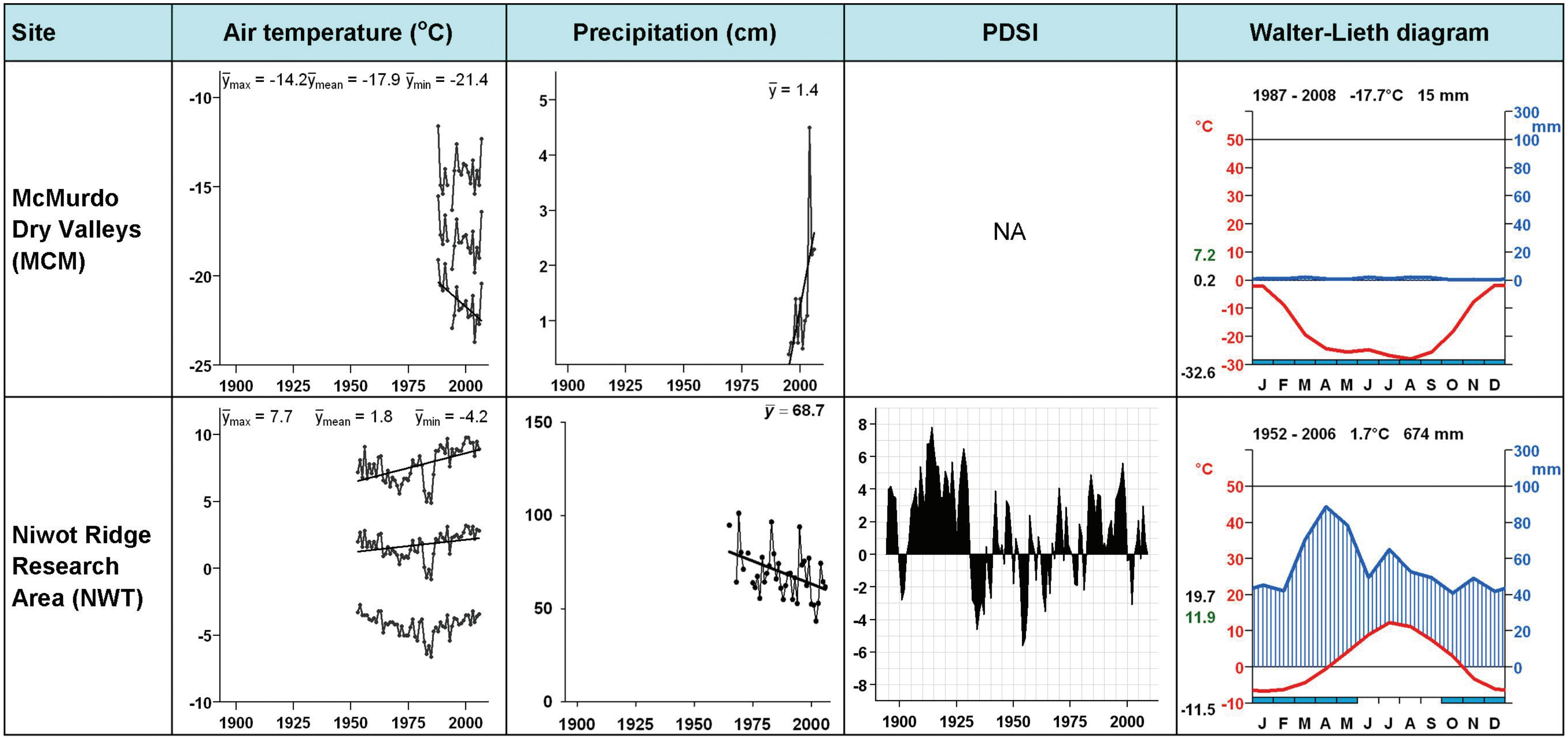


Figure 11-4. Trends for each alpine and arctic site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). 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.

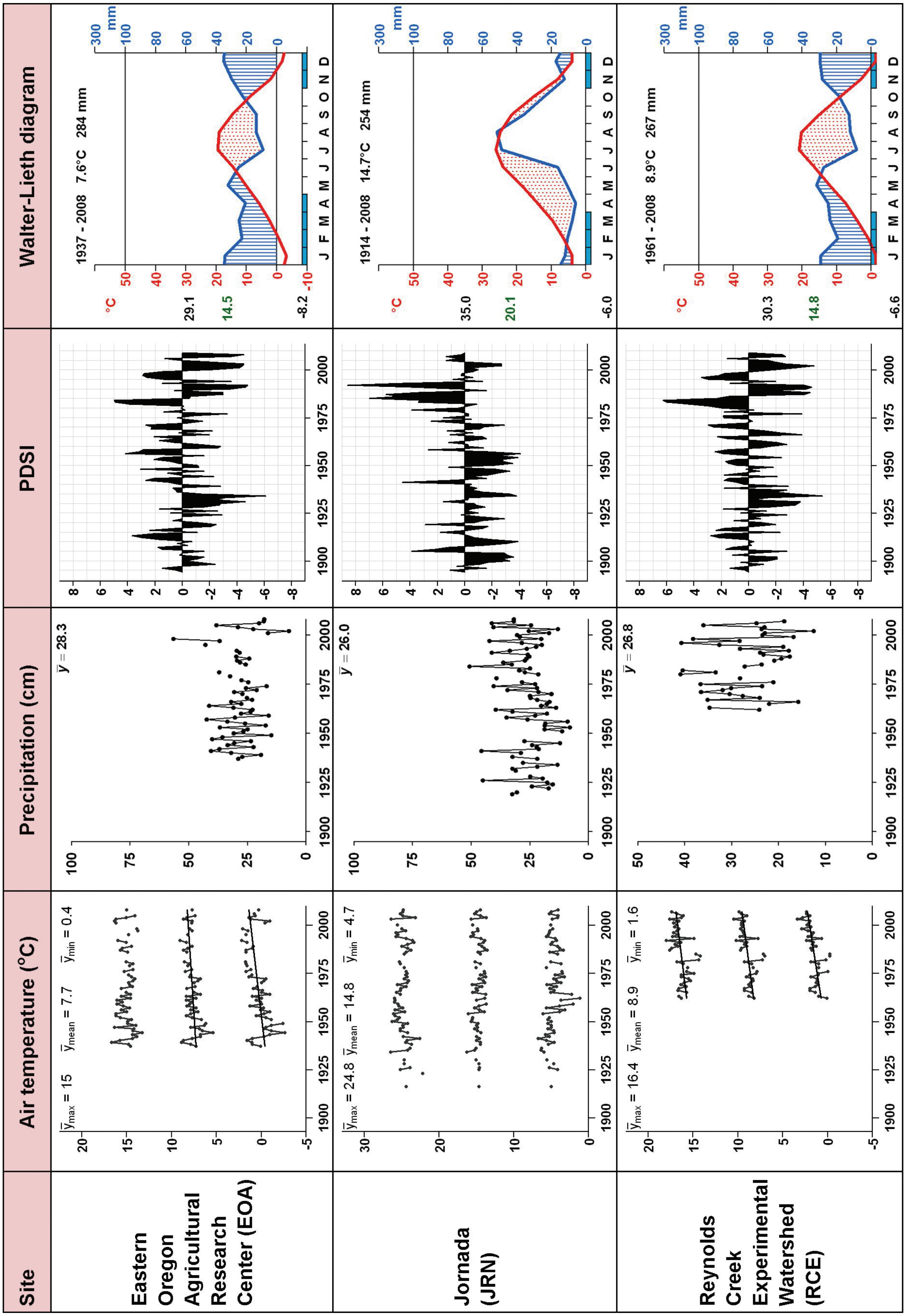


Figure 11-5 (aridland sites) continued next page.

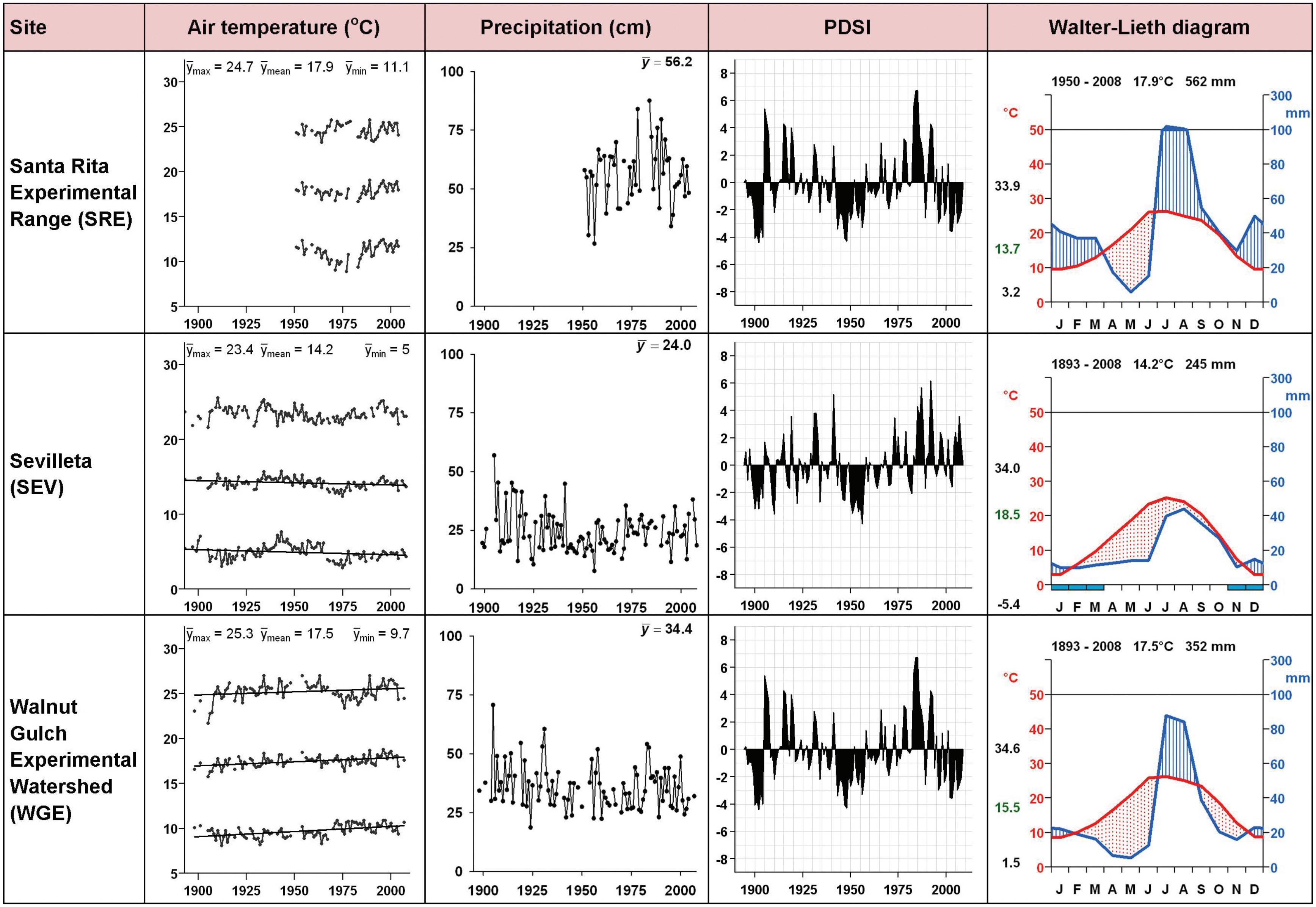


Figure 11-5. Trends for each aridland site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). 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.

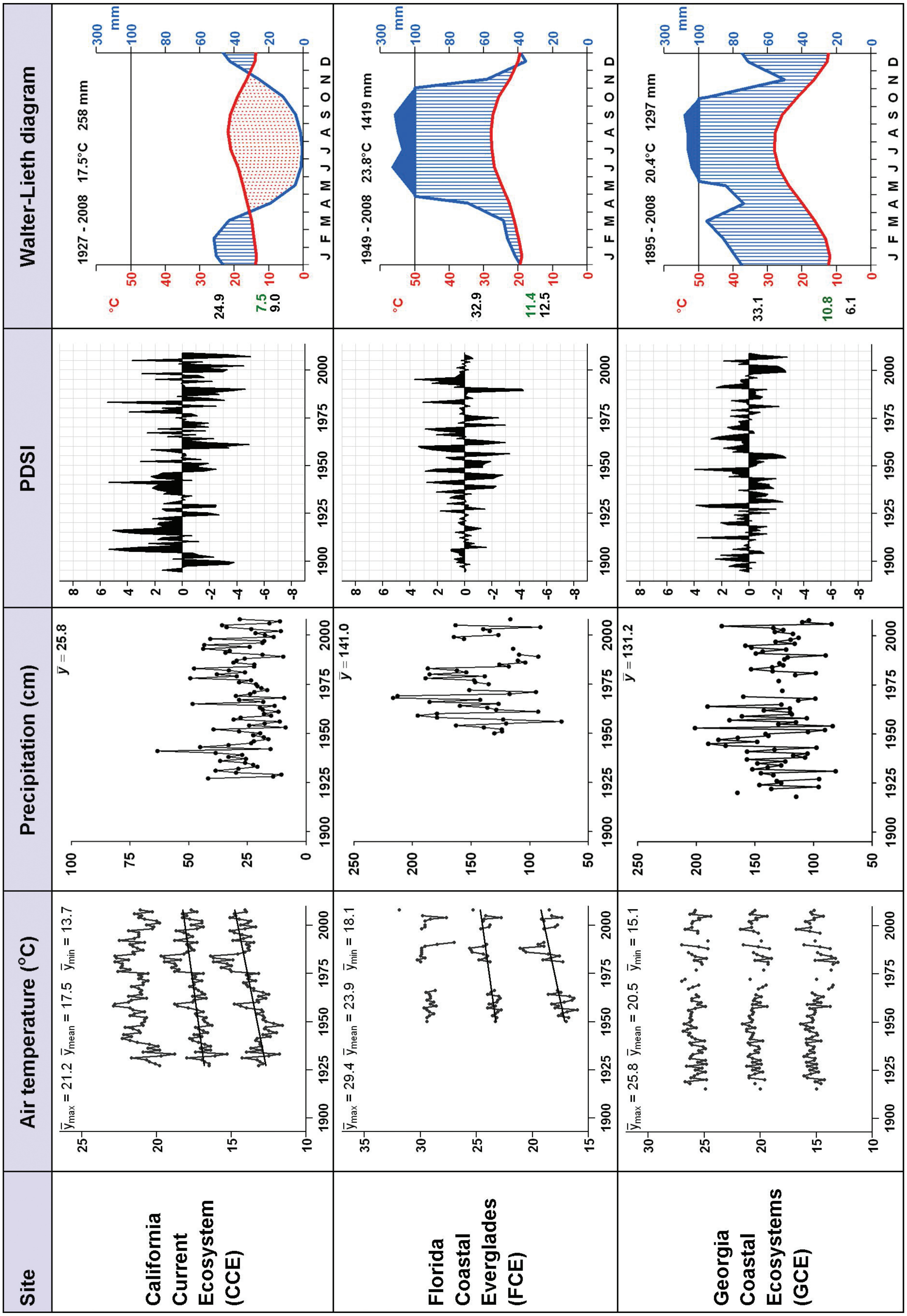
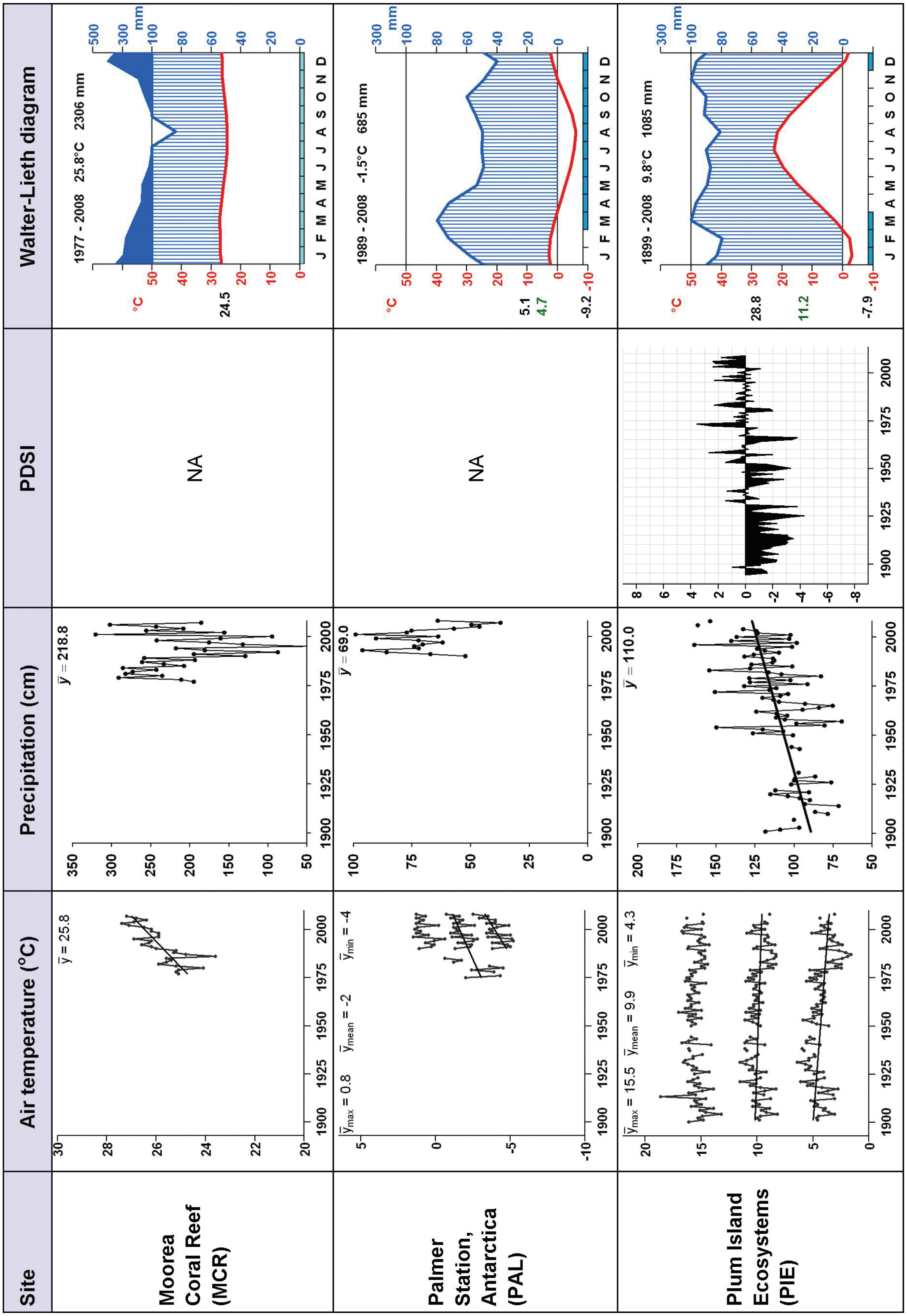


Figure 11-6 (coastal sites) continued next page.



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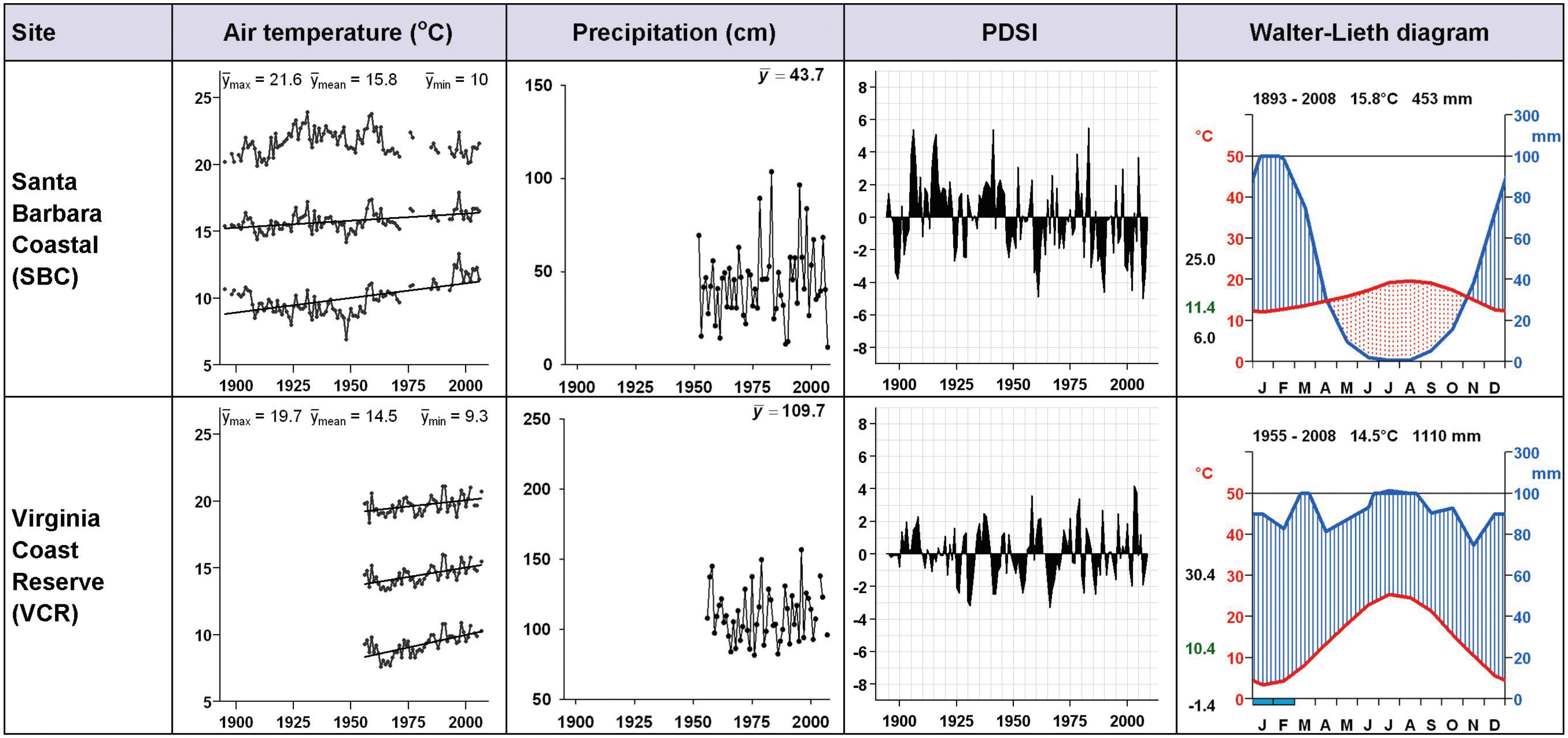


Figure 11-6. Trends for each coastal site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). 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.

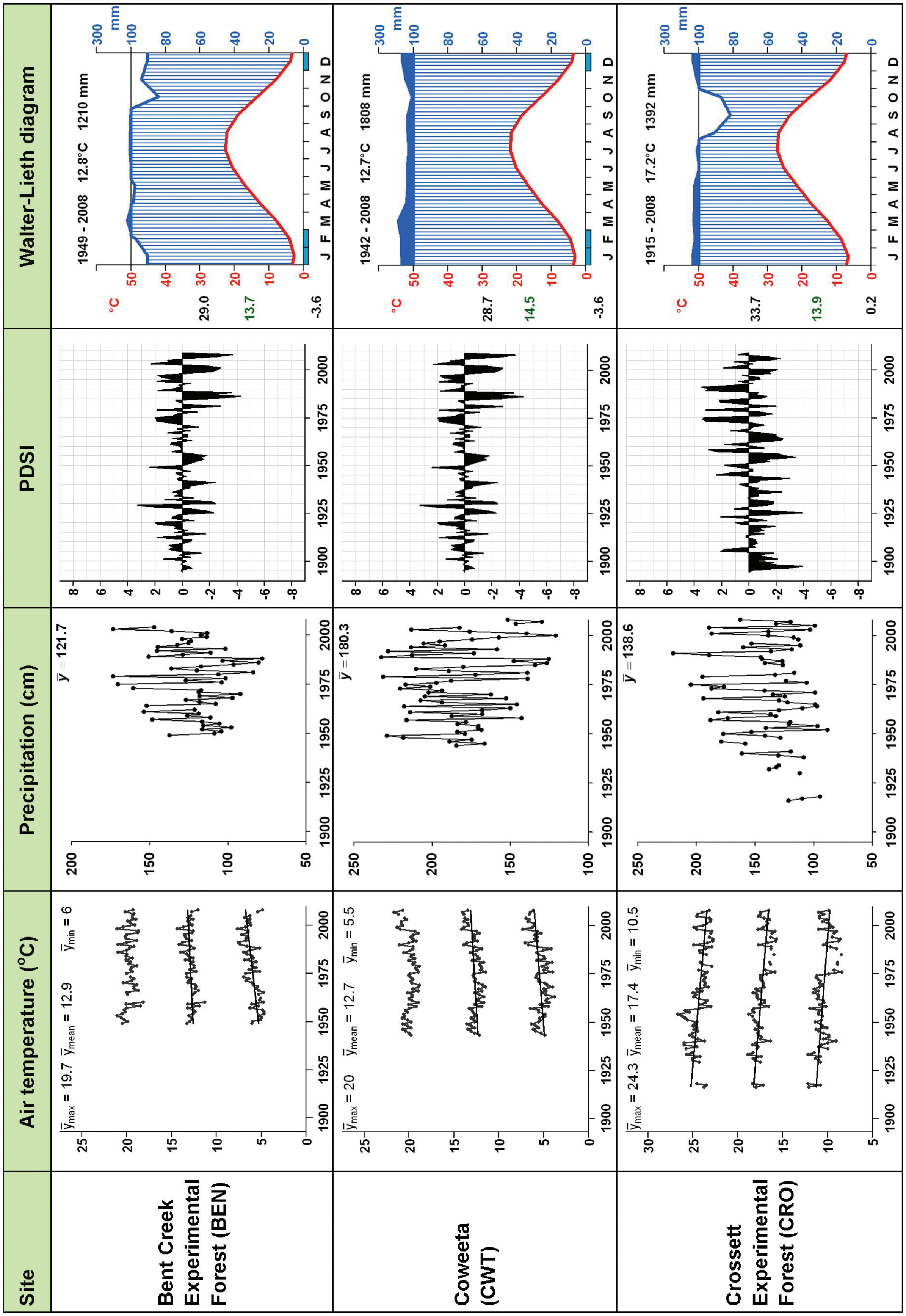
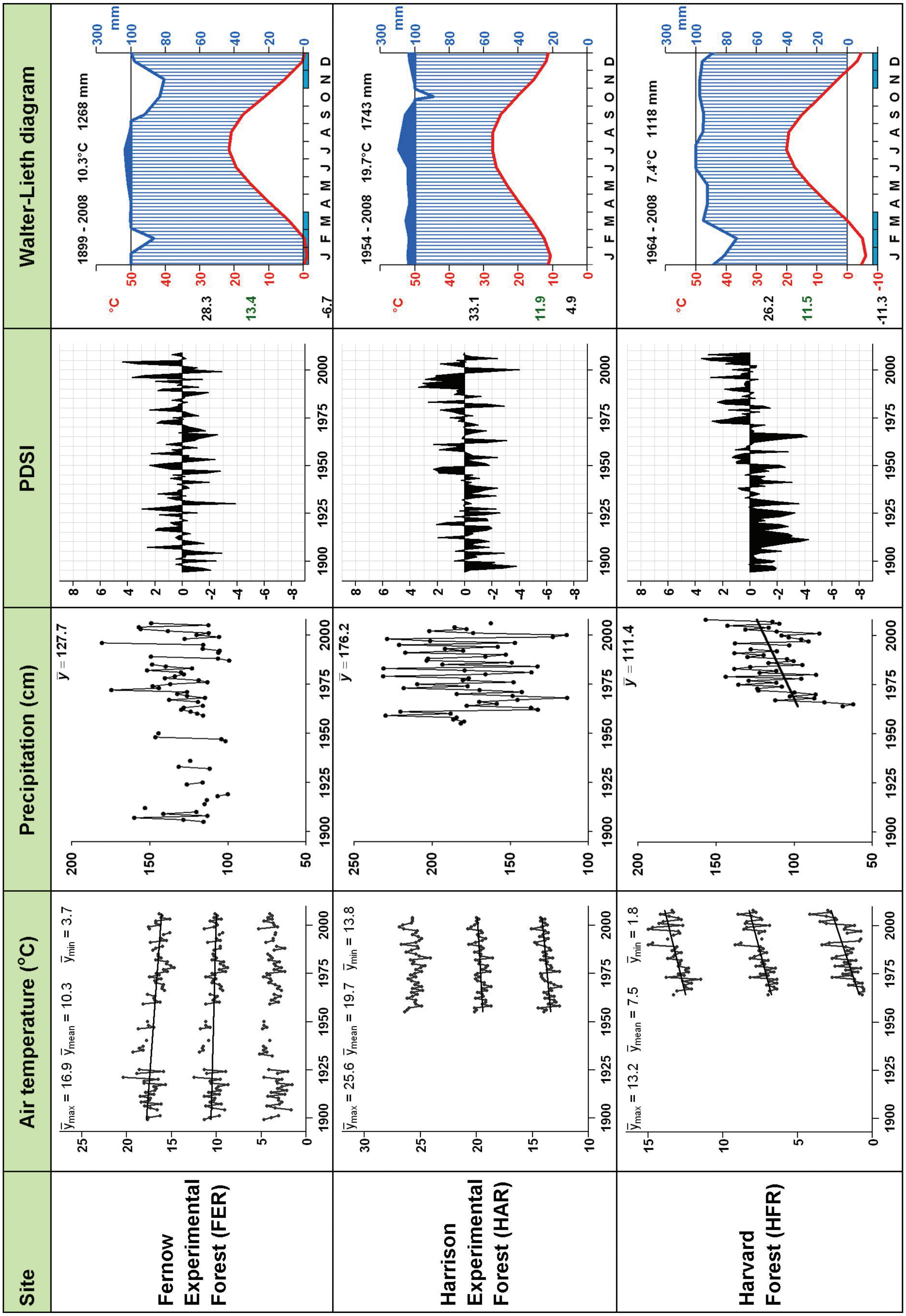


Figure 11-7 (eastern forest sites) continued next page.



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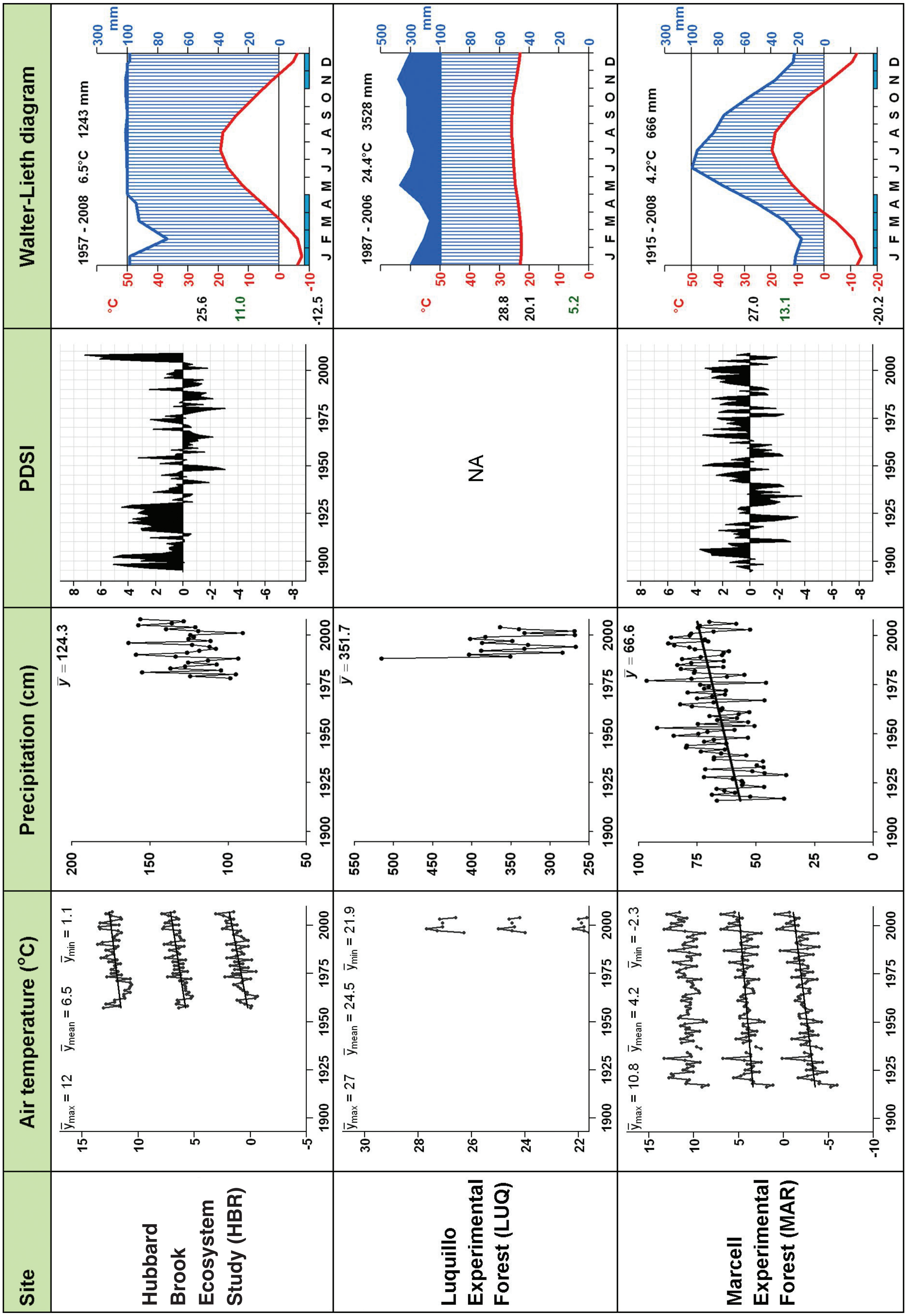

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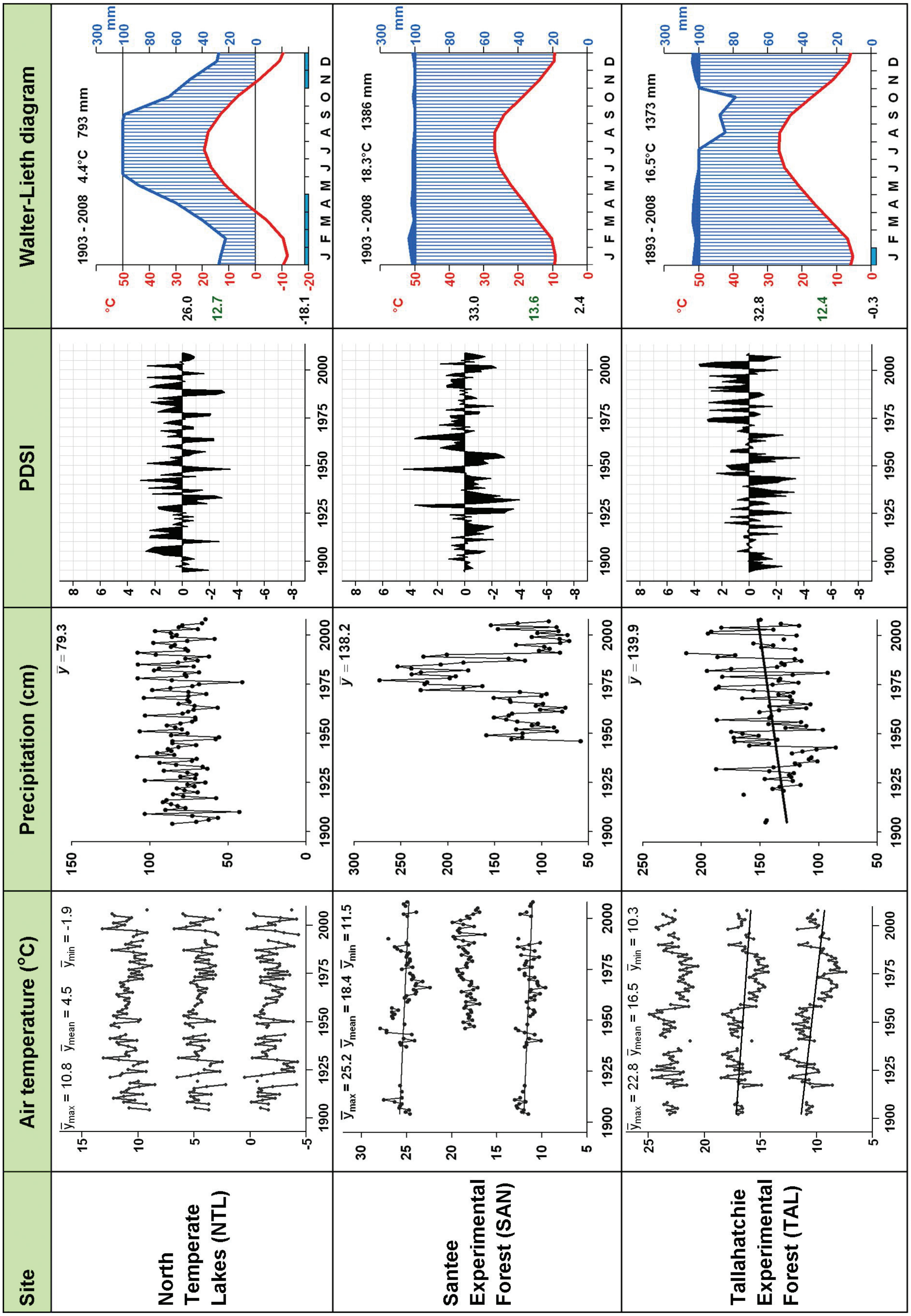

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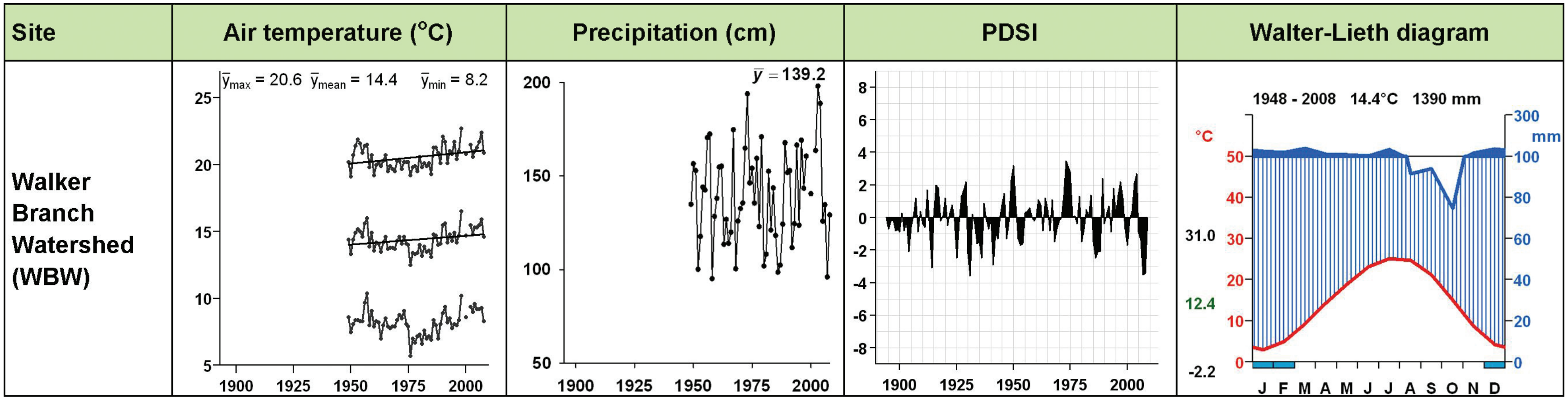


Figure 11-7. Trends for each eastern forest site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). 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.

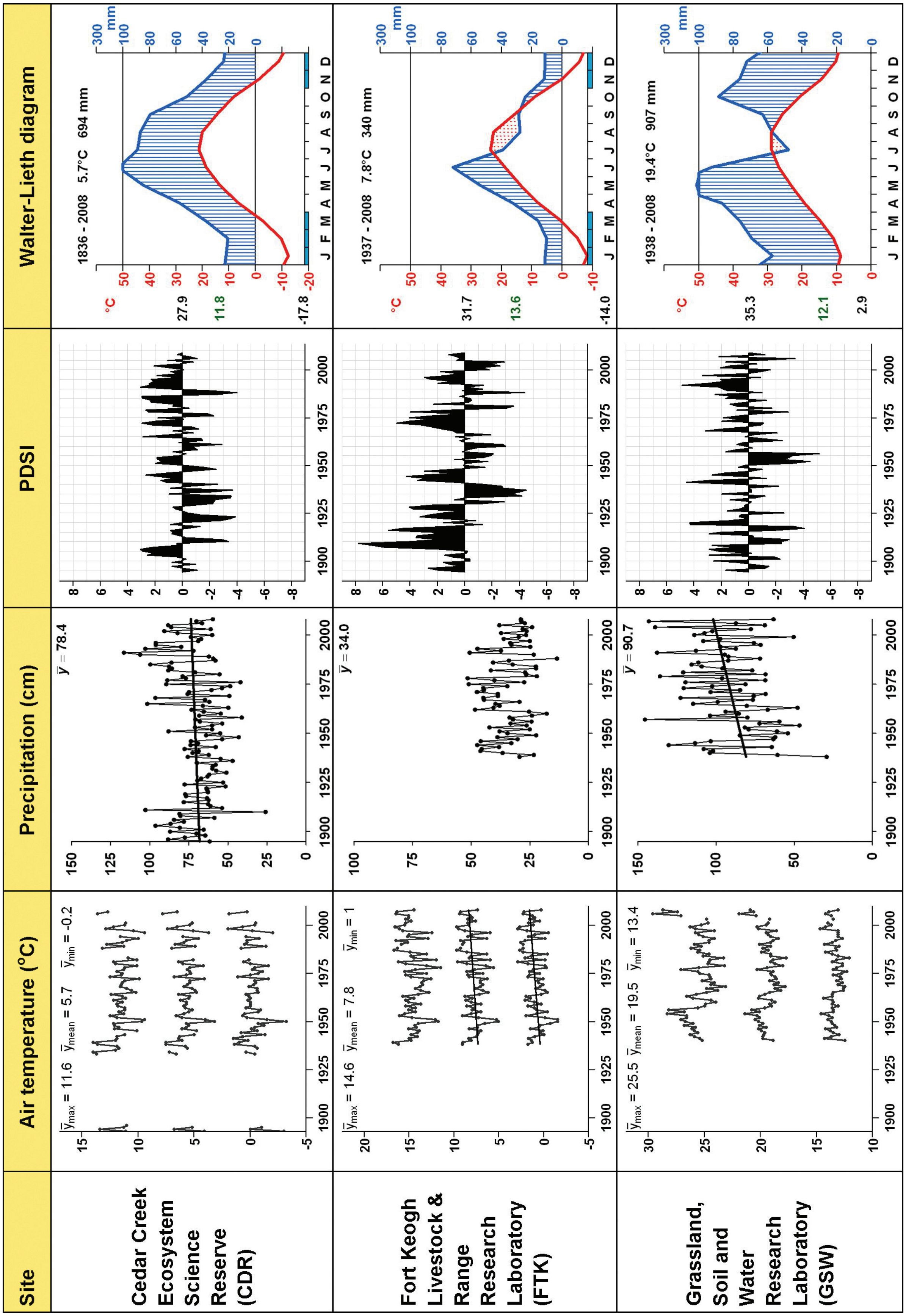


Figure 11-8 (grassland and savanna sites) continued next page.

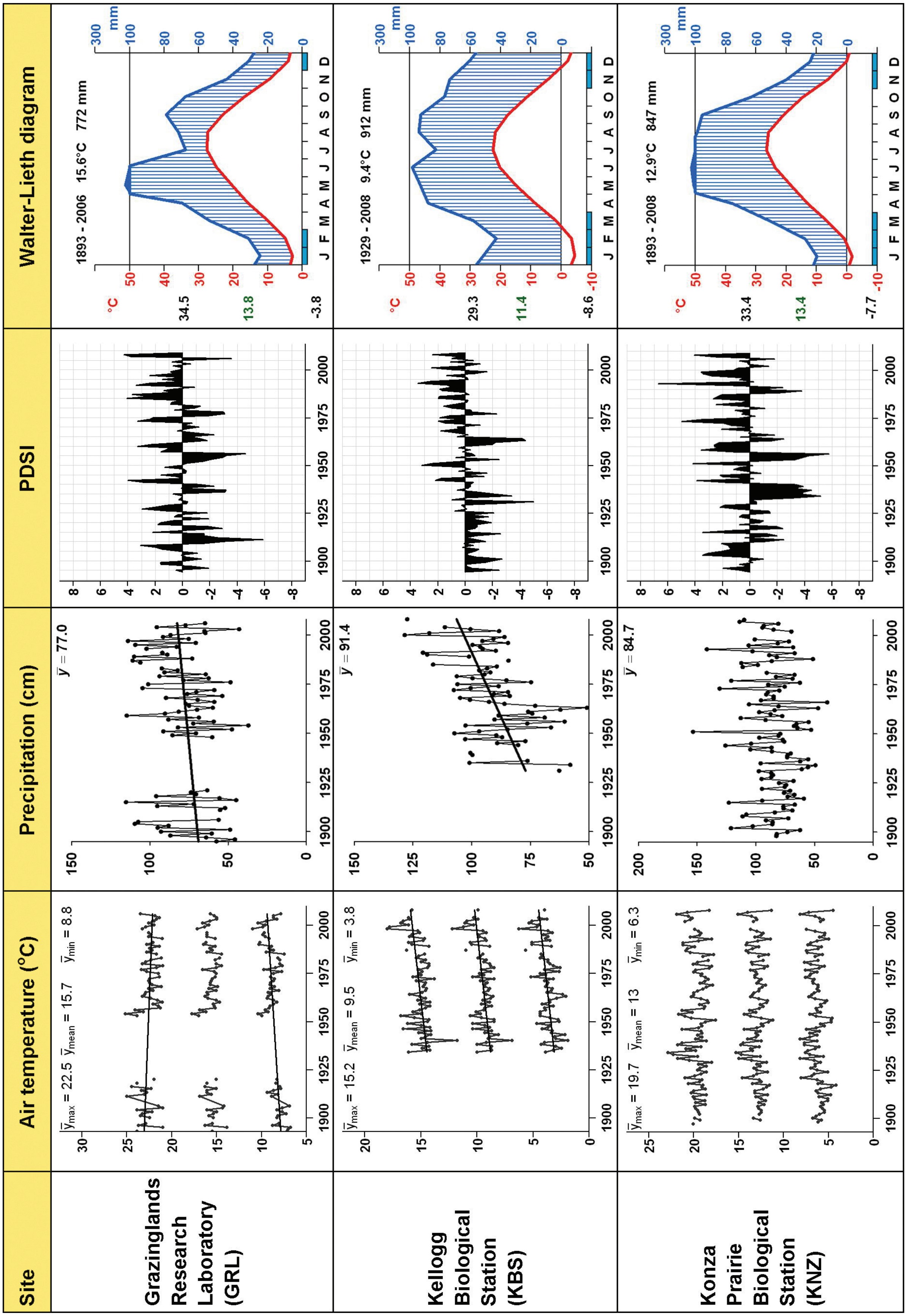


Figure 11-8 (grassland and savanna sites) continued next page.

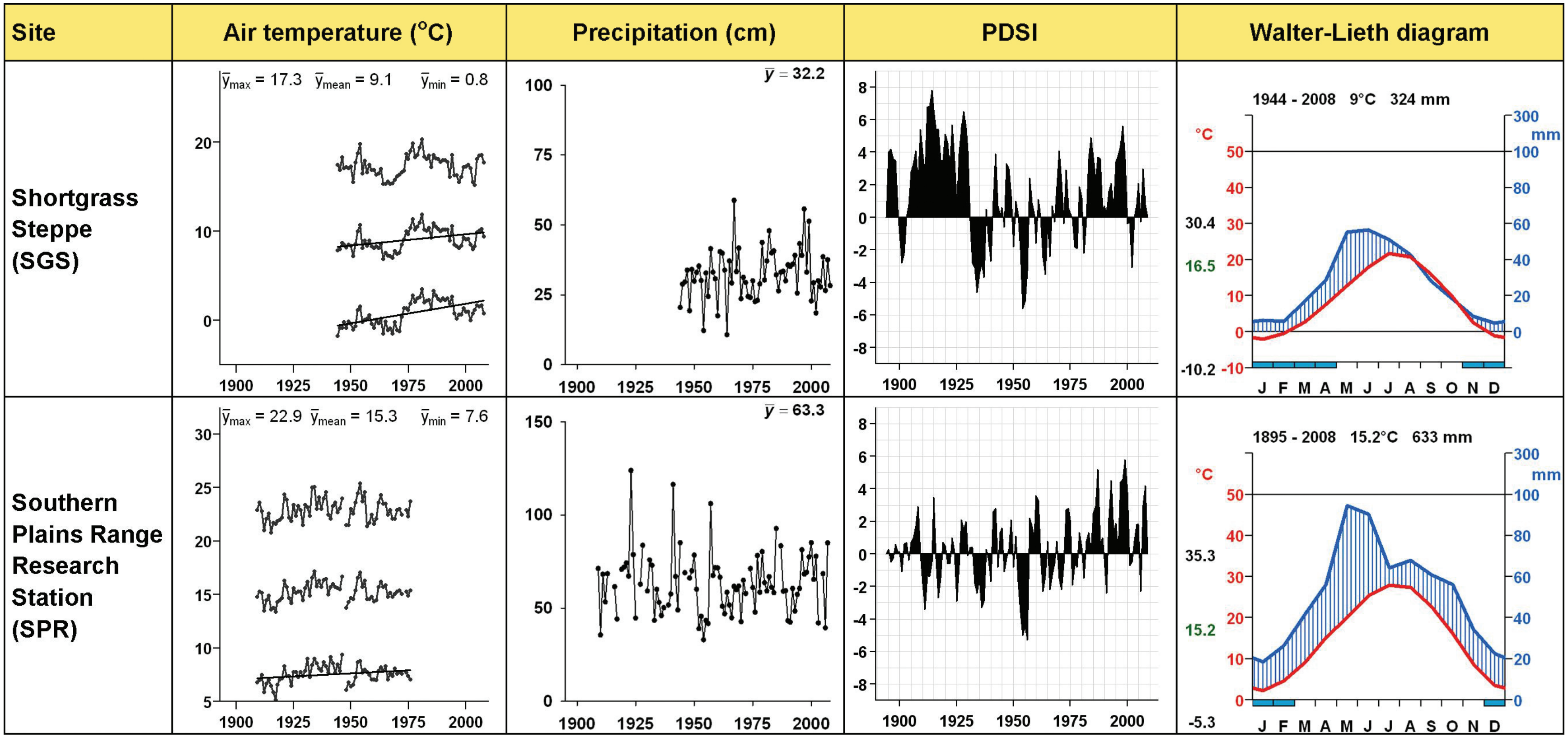


Figure 11-8. Trends for each temperate grassland and savanna site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically 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.

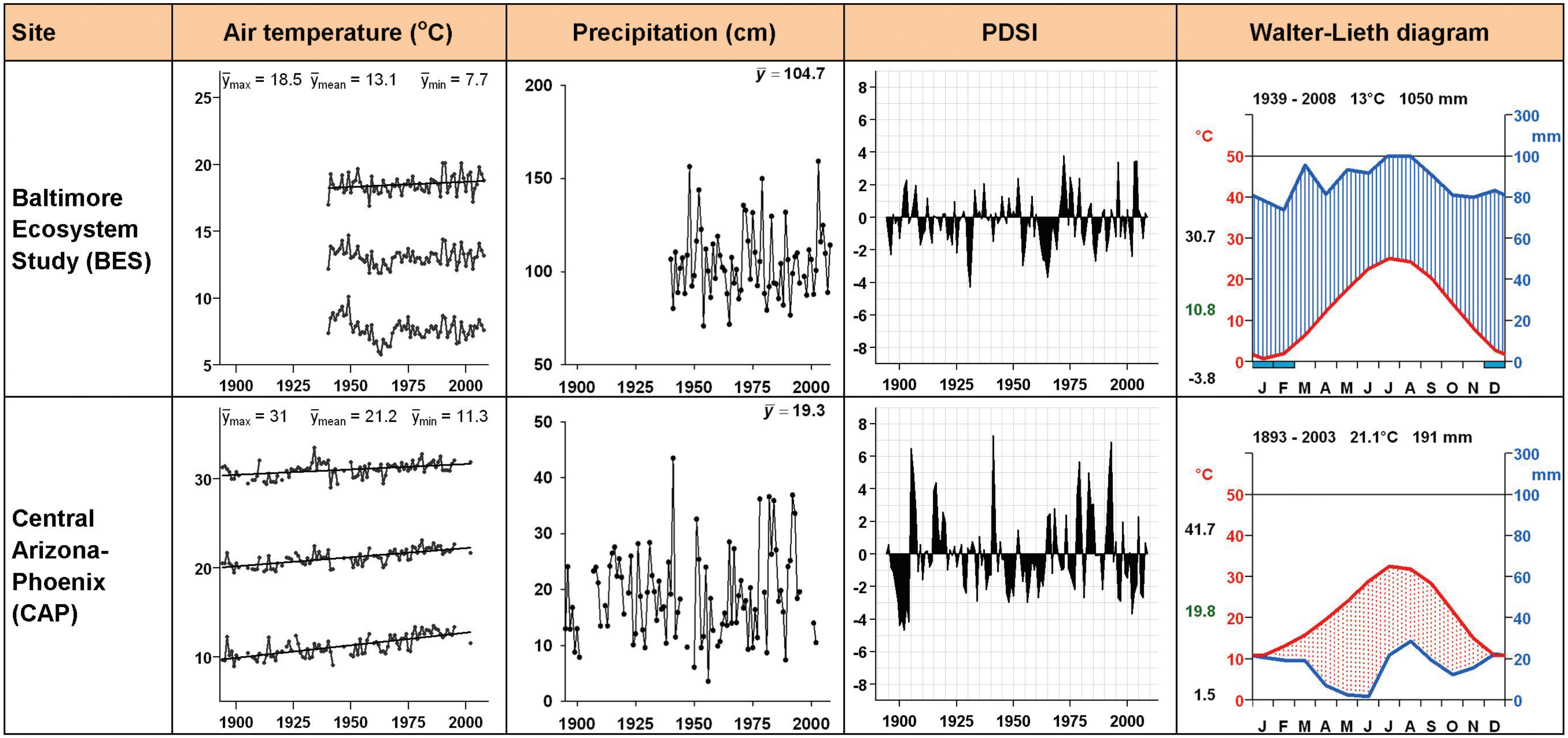


Figure 11-9. Trends for each urban site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). 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.

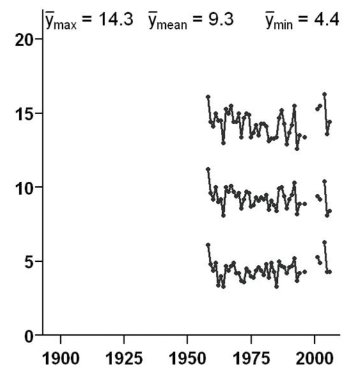
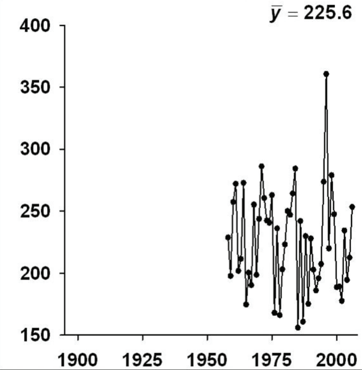
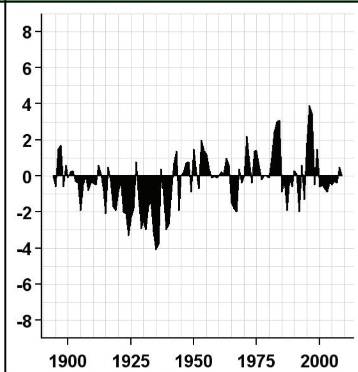
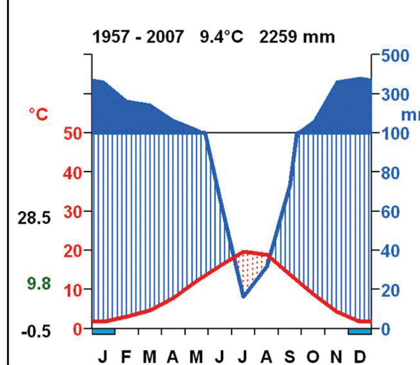
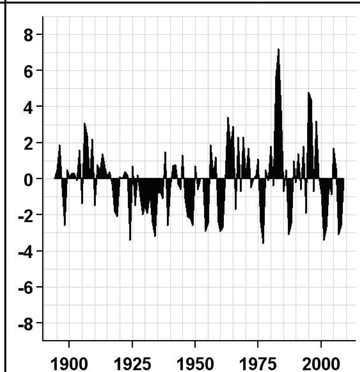
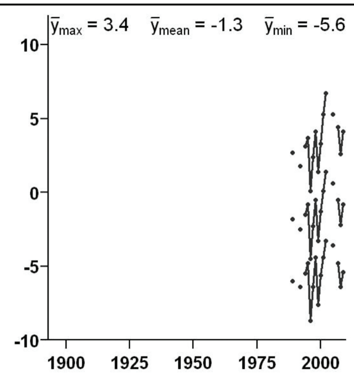
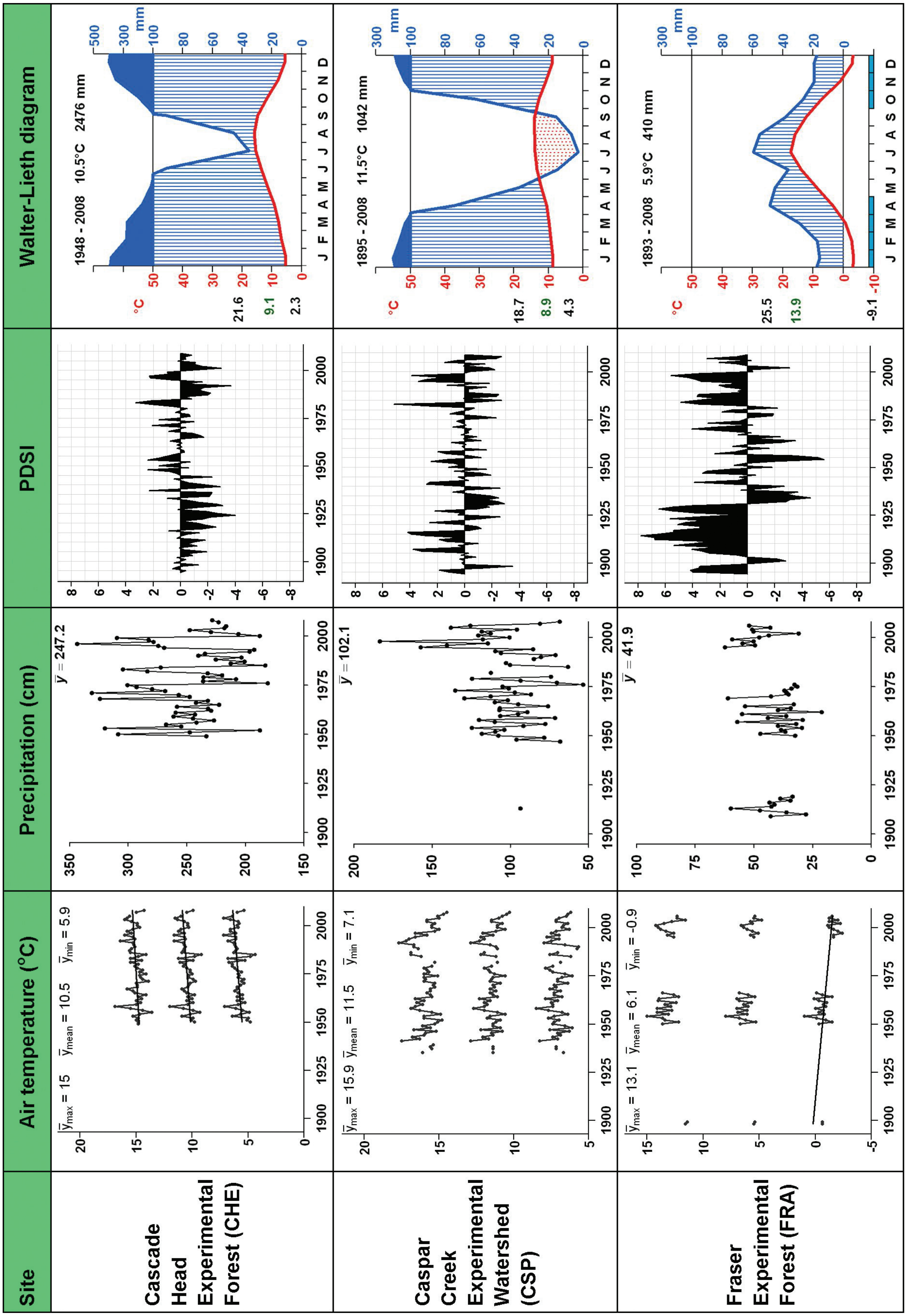
Site	Air temperature (°C)	Precipitation (cm)	PDSI	Walter-Lieth diagram
Andrews Experimental Forest (AND)				
Blacks Mountain Experimental Forest (BLA)	NA	NA		NA
Bonanza Creek Experimental Forest (BNZ)		NA	NA	NA

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



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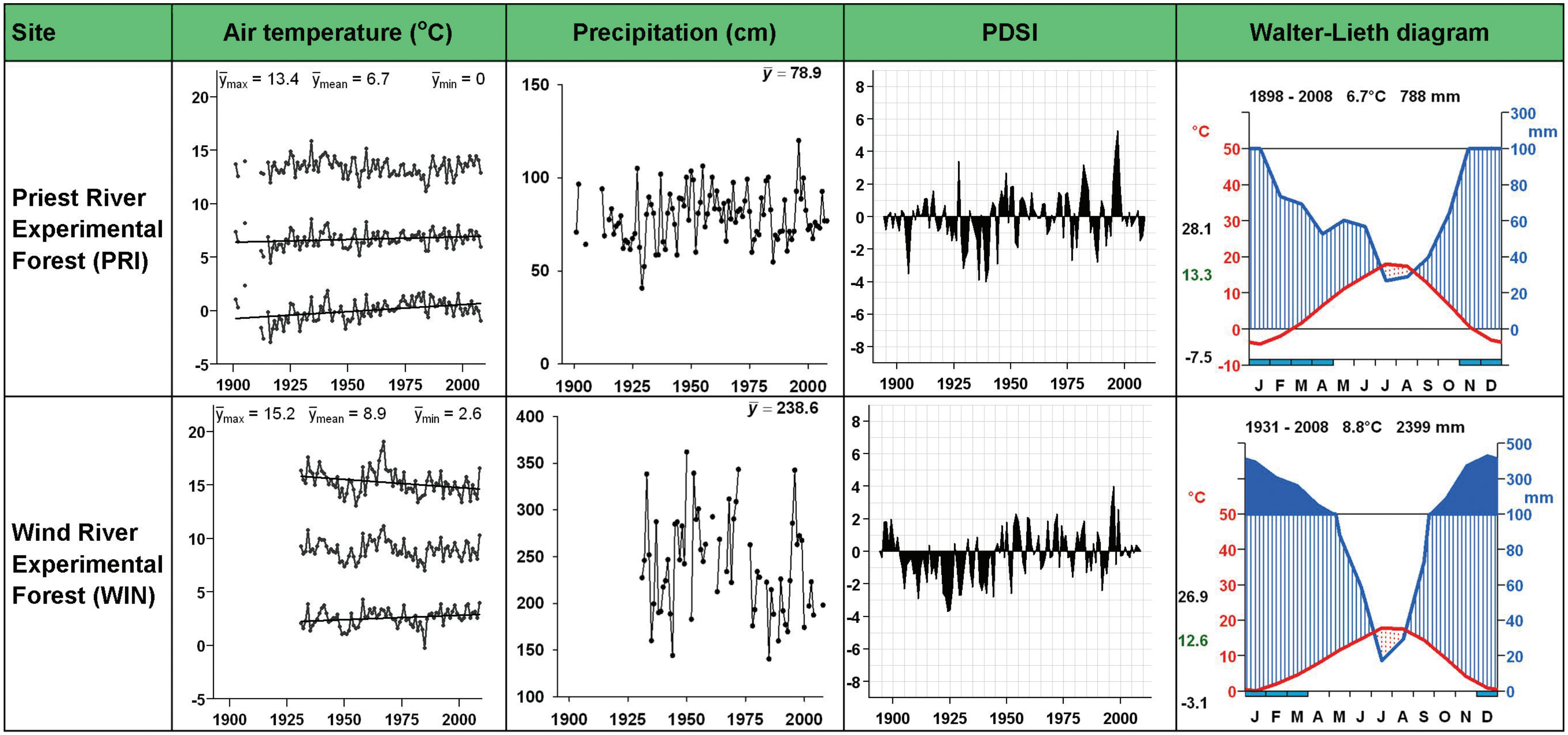

Figure 11-10. Trends for each western forest site—annual temperature (°C) (minimum, mean, maximum), annual precipitation (cm), annual PDSI, and monthly average precipitation and mean temperature—in a Walter-Lieth diagram. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). 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.

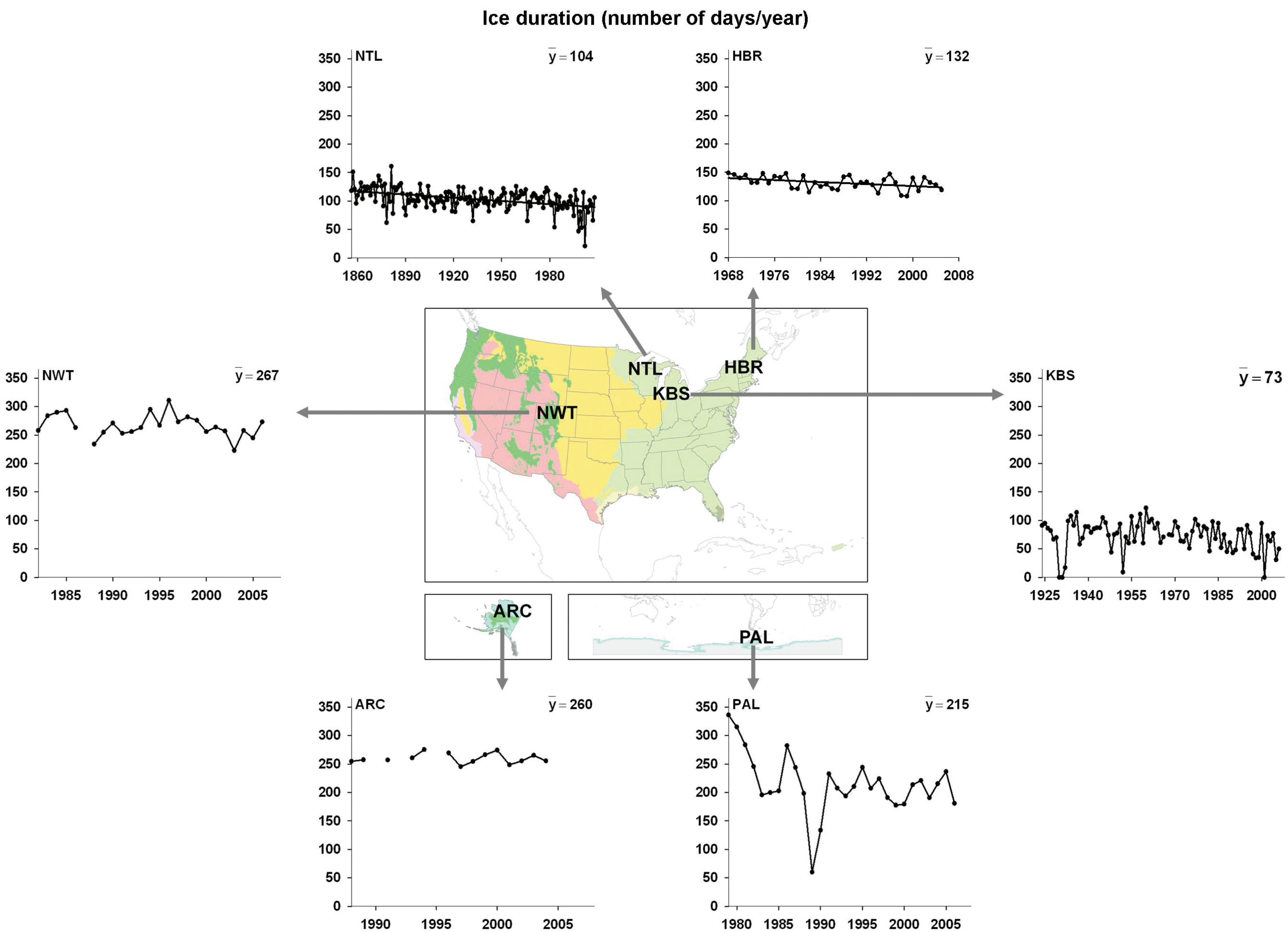

Figure 11-11. Ice duration (number of days per year) through time and the mean number of days per year for six sites with data. Length of the time series differs among sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Hubbard 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.

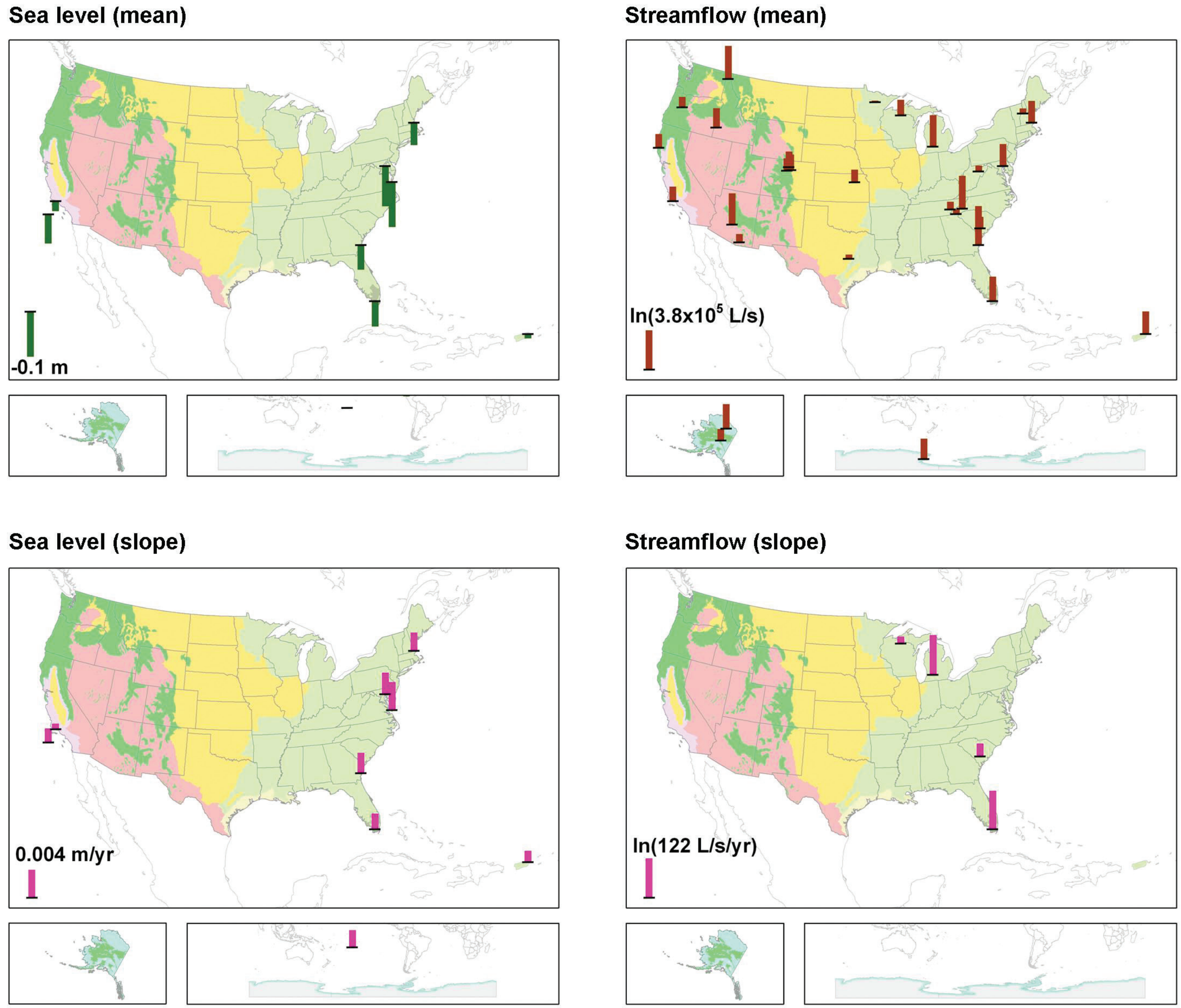

Figure 11-12. Continental patterns in annual mean sea level (m) and streamflow (L/s). Annual mean sea level is defined as the annual arithmetic mean of hourly heights relative to the National Tidal Datum Epoch (the most recent mean sea level datum established by the Center for Operational Oceanographic 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.

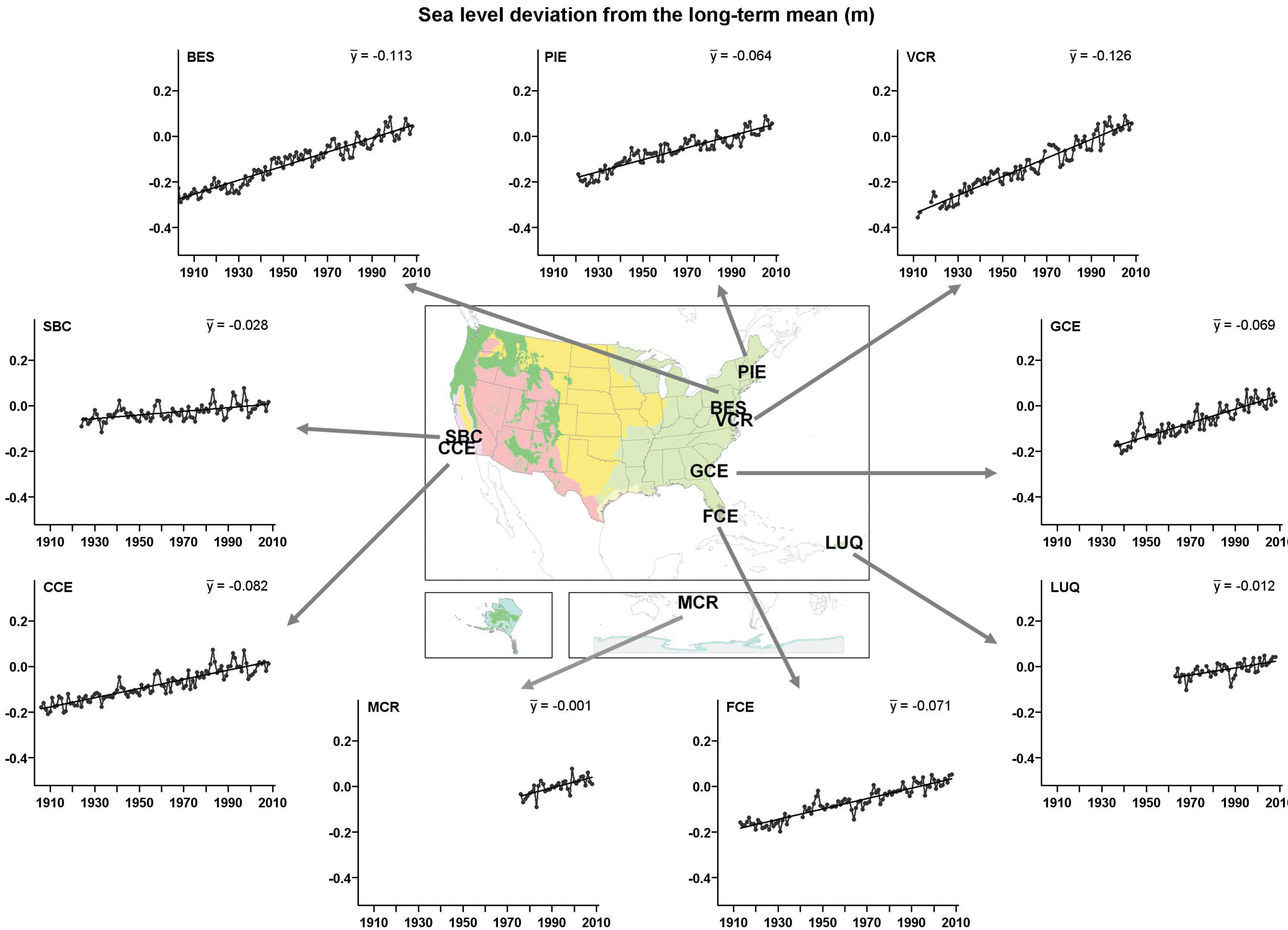

Figure 11-13. Annual mean sea level (m) through time for nine sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Santa Barbara Coastal (SBC): 0.001; California Current Ecosystem (CCE), Florida Coastal Everglades (FCE), and Luquillo 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.

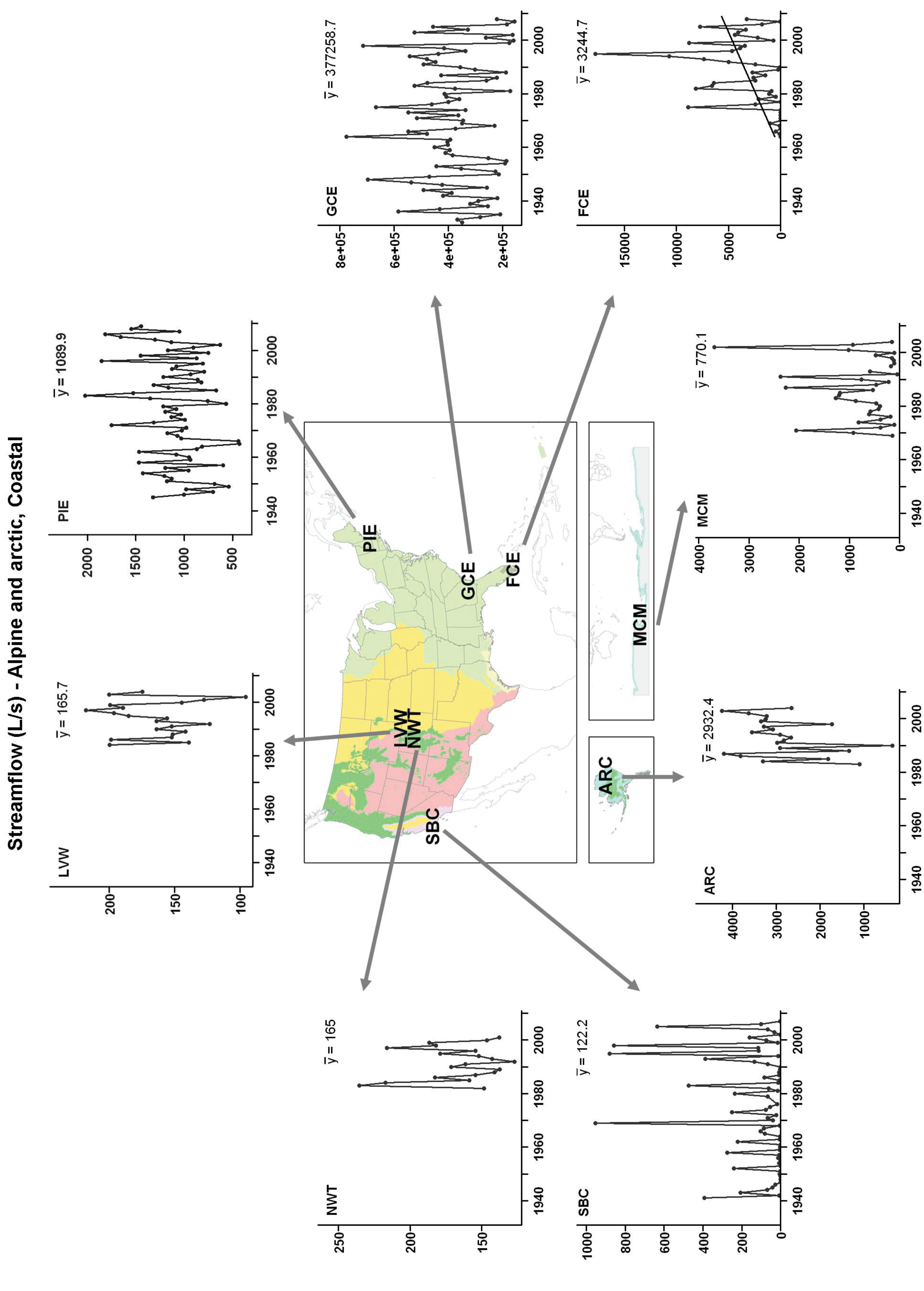

Figure 11-14. Streamflow (L/s) through time for eight alpine and arctic sites and coastal sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slope is Florida Coastal Everglades (FCE) (110.6). Original data from Internet home pages (see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

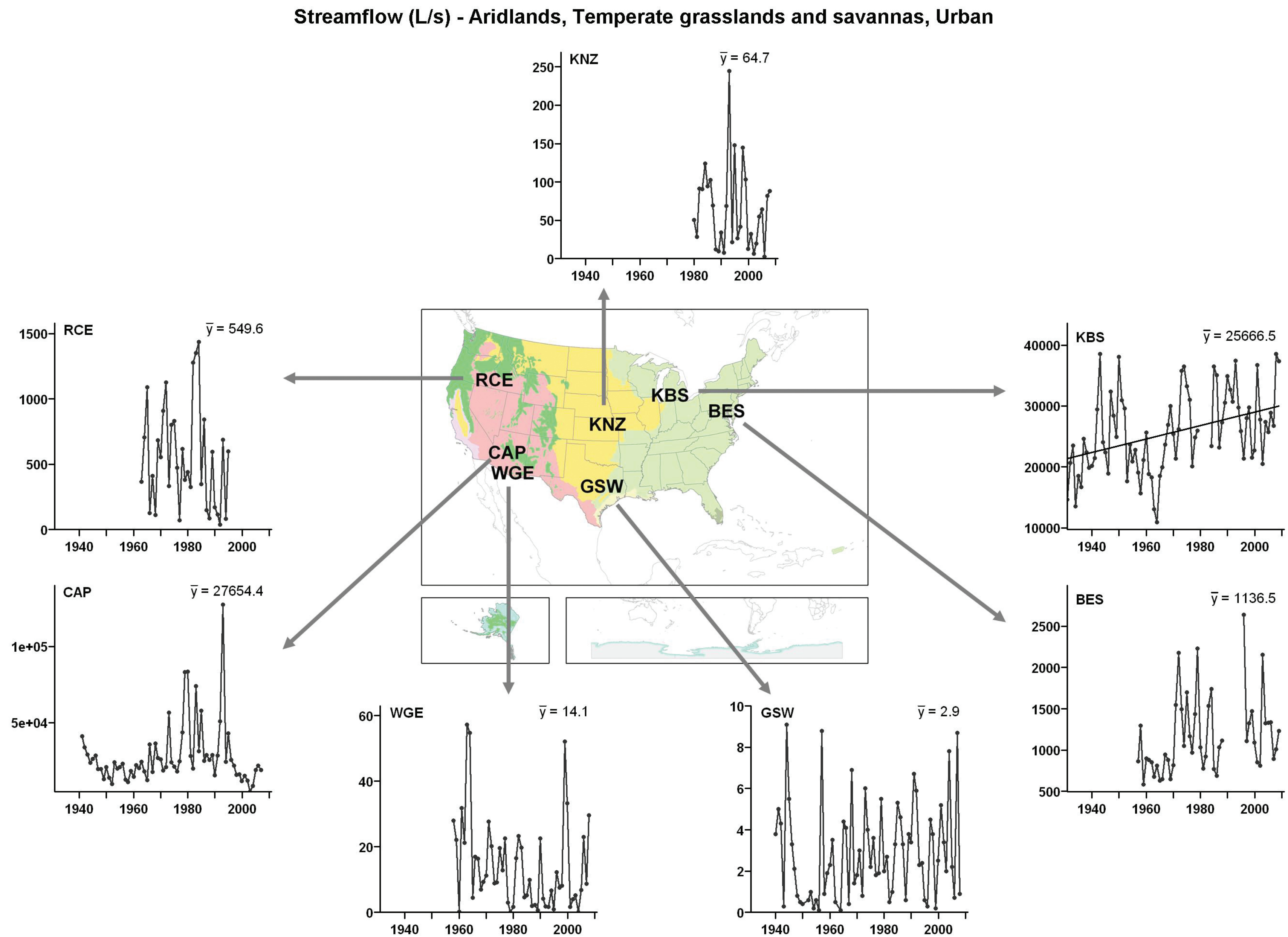

Figure 11-15. Streamflow (L/s) through time for seven aridland, temperate grassland and savanna, and urban sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slope is Kellogg Biological Station (KBS) (122.1). Original data from Internet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

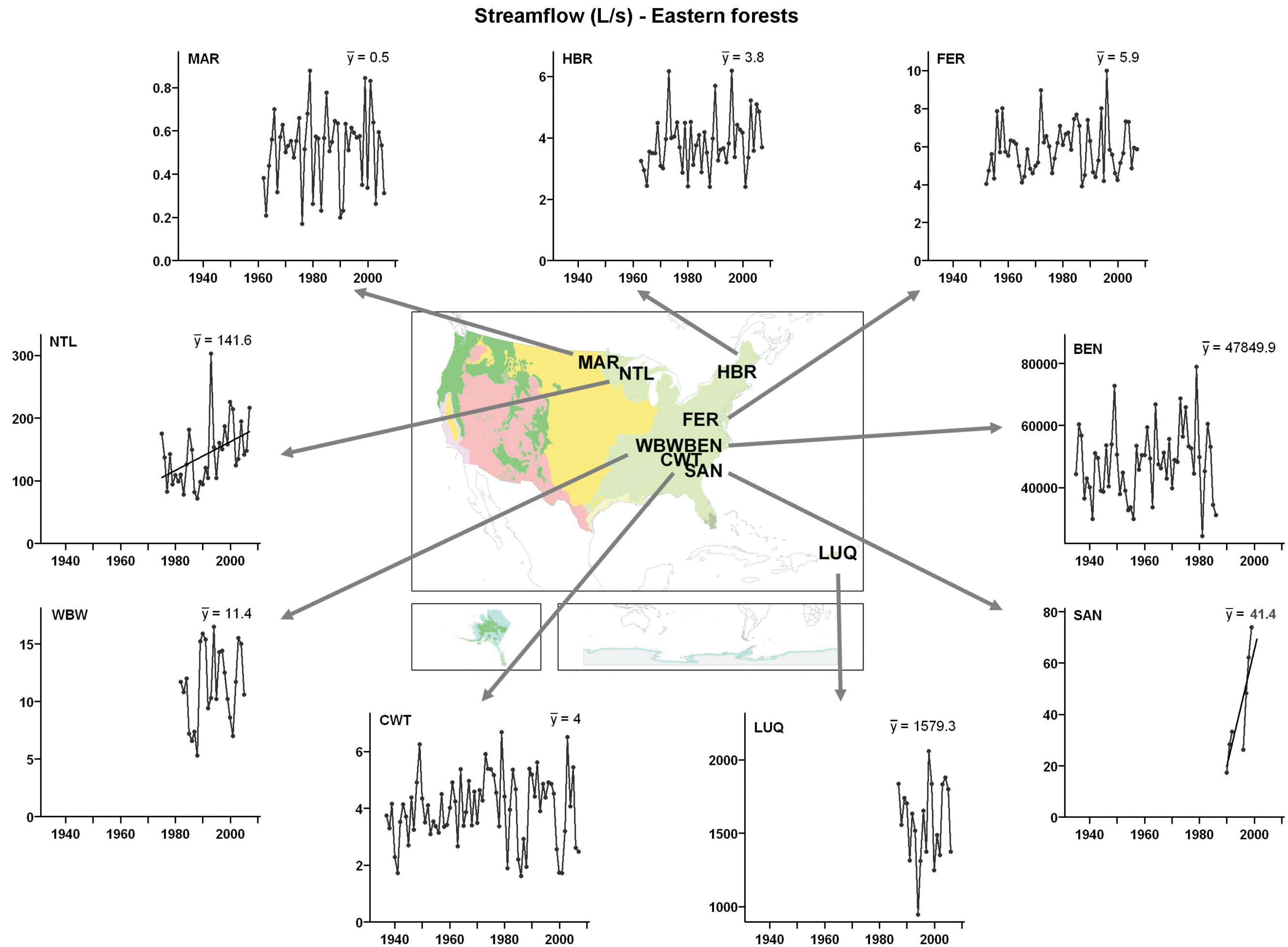

Figure 11-16. Streamflow (L/s) through time for nine eastern forest sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are North Temperate Lakes (NTL) (2.3) and Santee Experimental Forest (SAN) (4.9). Original data from Internet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

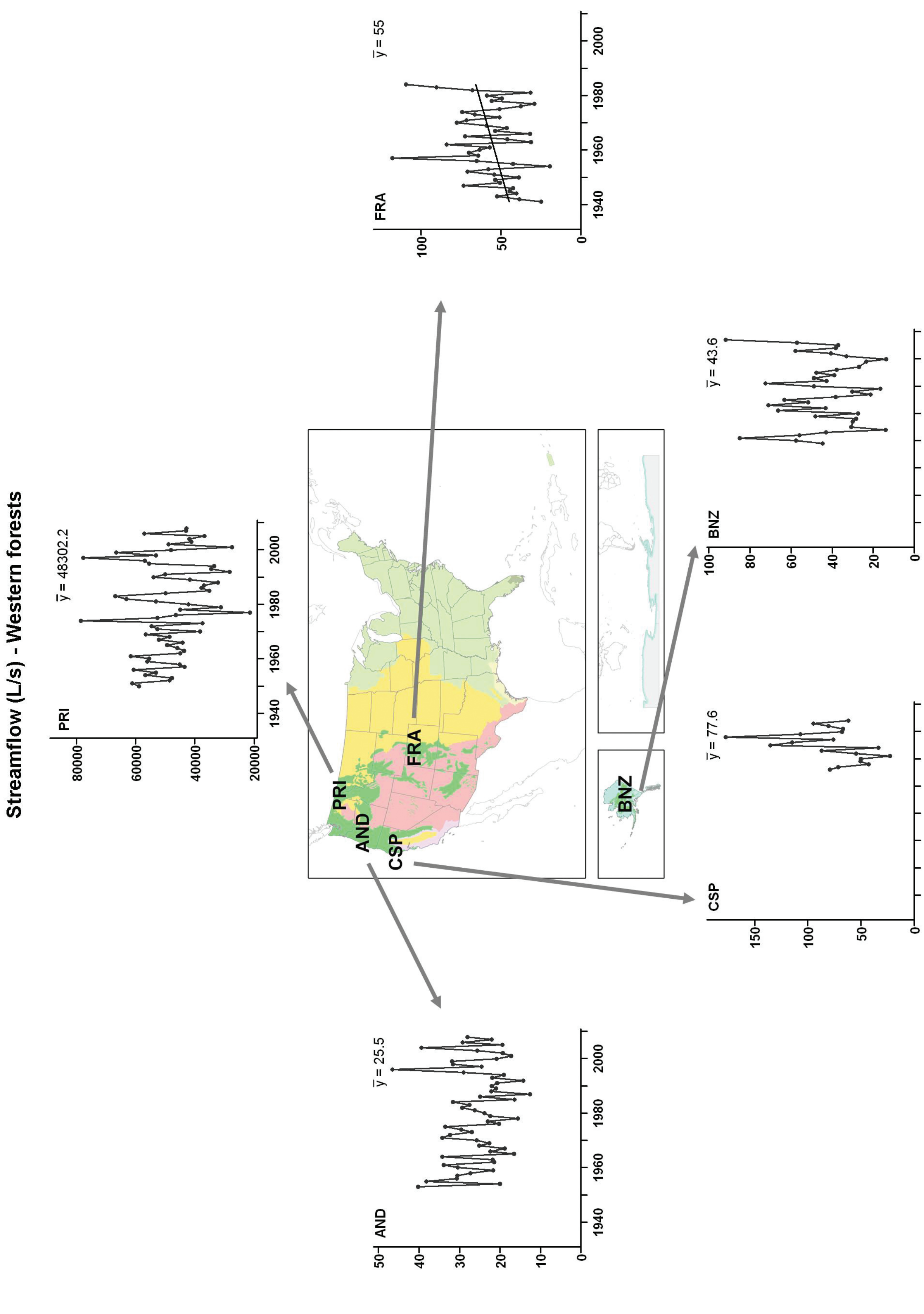

Figure 11-17. Streamflow (L/s) through time for five western forest sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

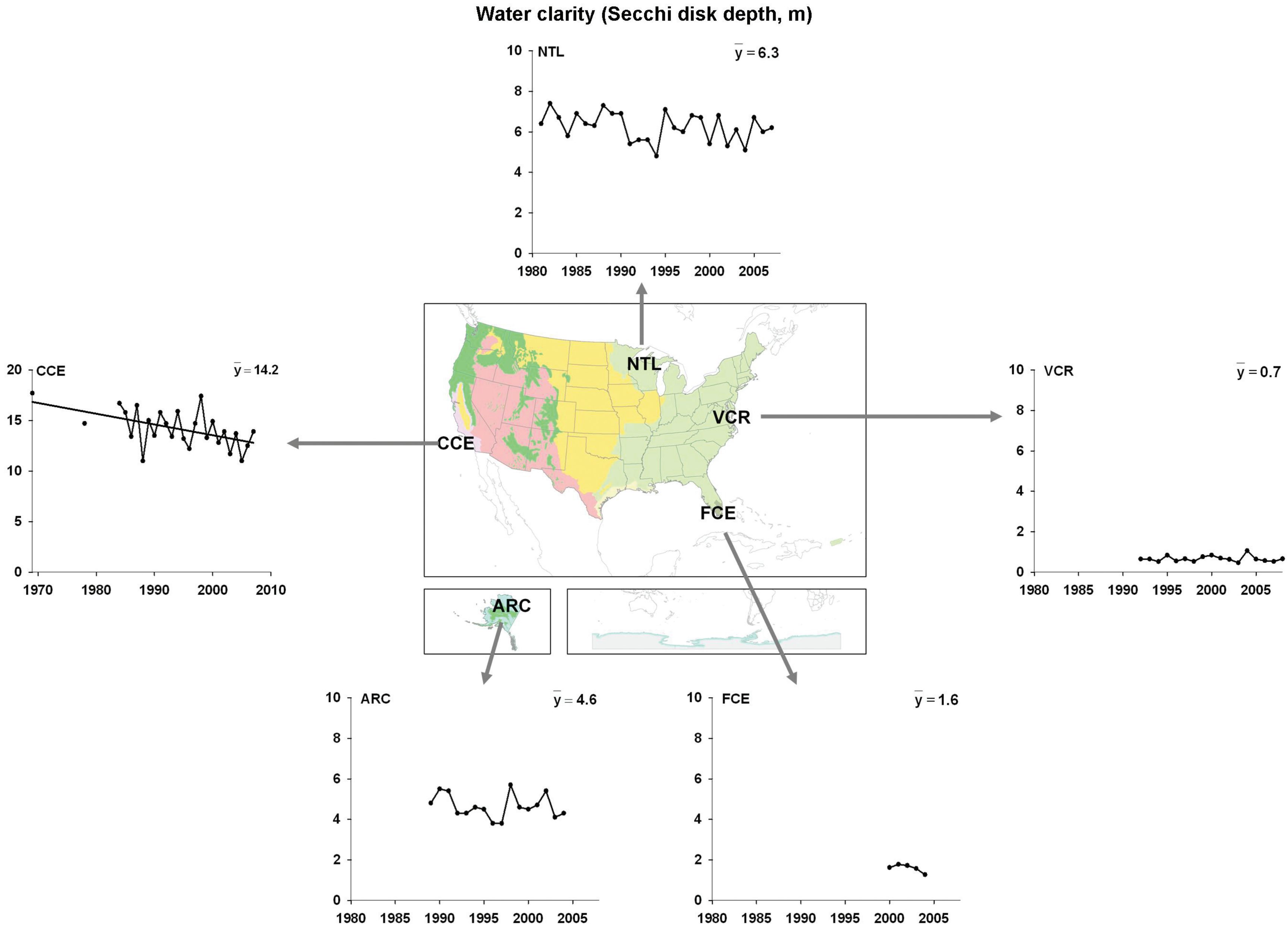

Figure 11-18. Water clarity (as Secchi disk depth, m) through time for five sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slope is California Current Ecosystem (CCE) (-0.1). Original data from Internet home pages (see table 1-1) and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

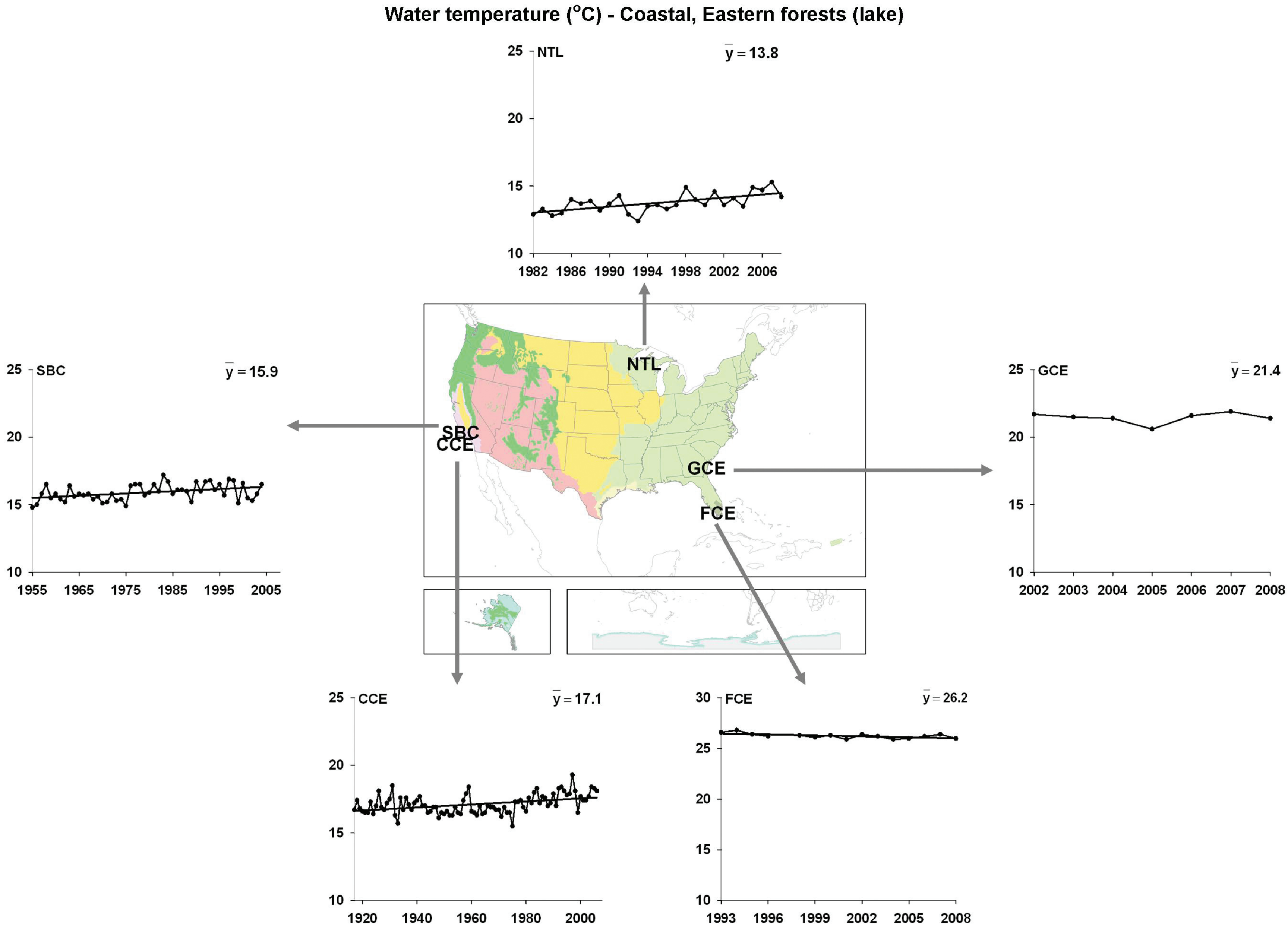

Figure 11-19. Water temperature (°C) through time for five coastal sites and one lake in an eastern forest site. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are: California Current Ecosystem (CCE) (0.01), Florida Coastal Everglades (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.

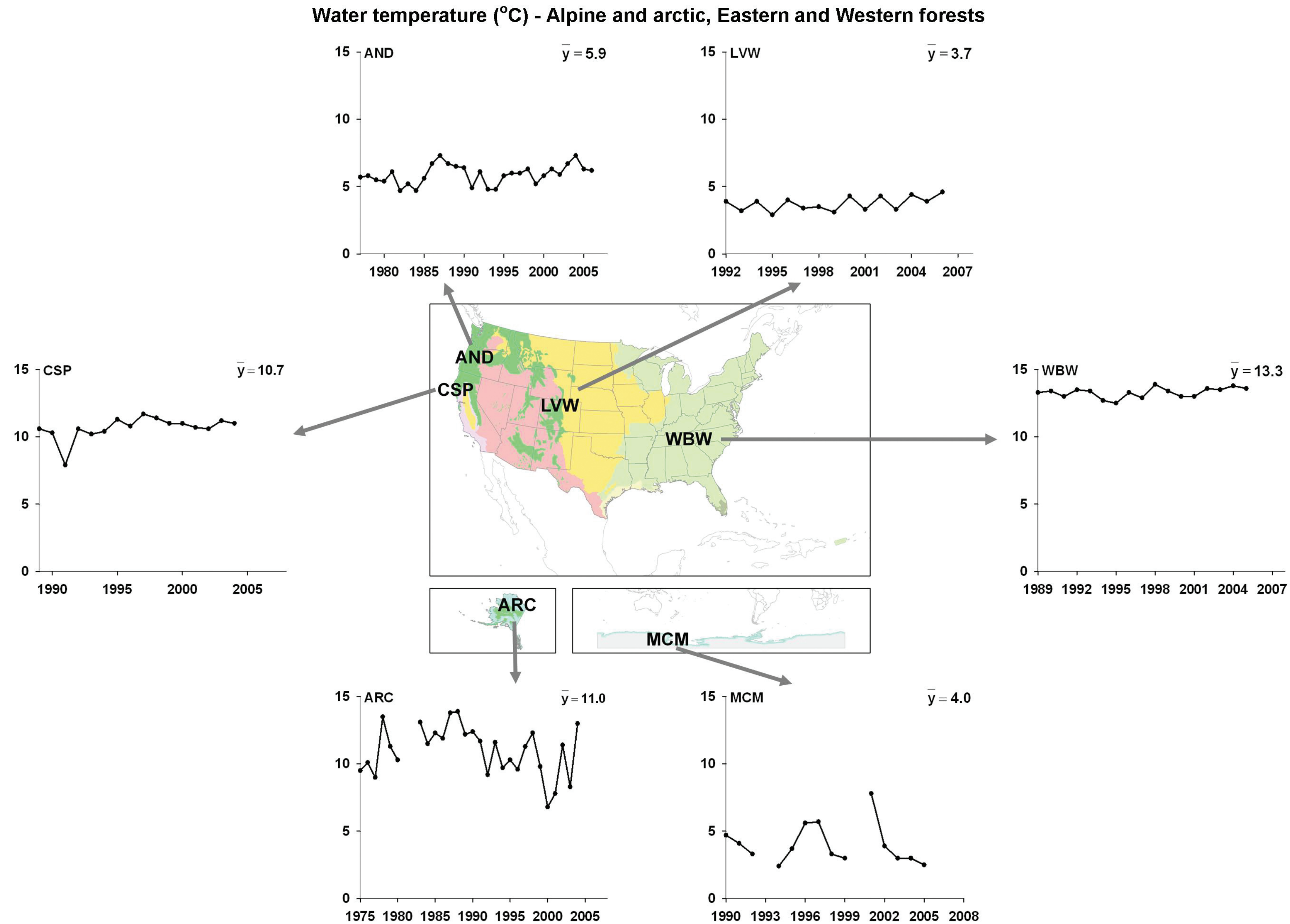

Figure 11-20. Water temperature (°C) through time for streams in six alpine and arctic sites and eastern and western forest sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). Original data from Internet home pages (see table 1-1) and http://www4.ncdc.noaa.gov.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

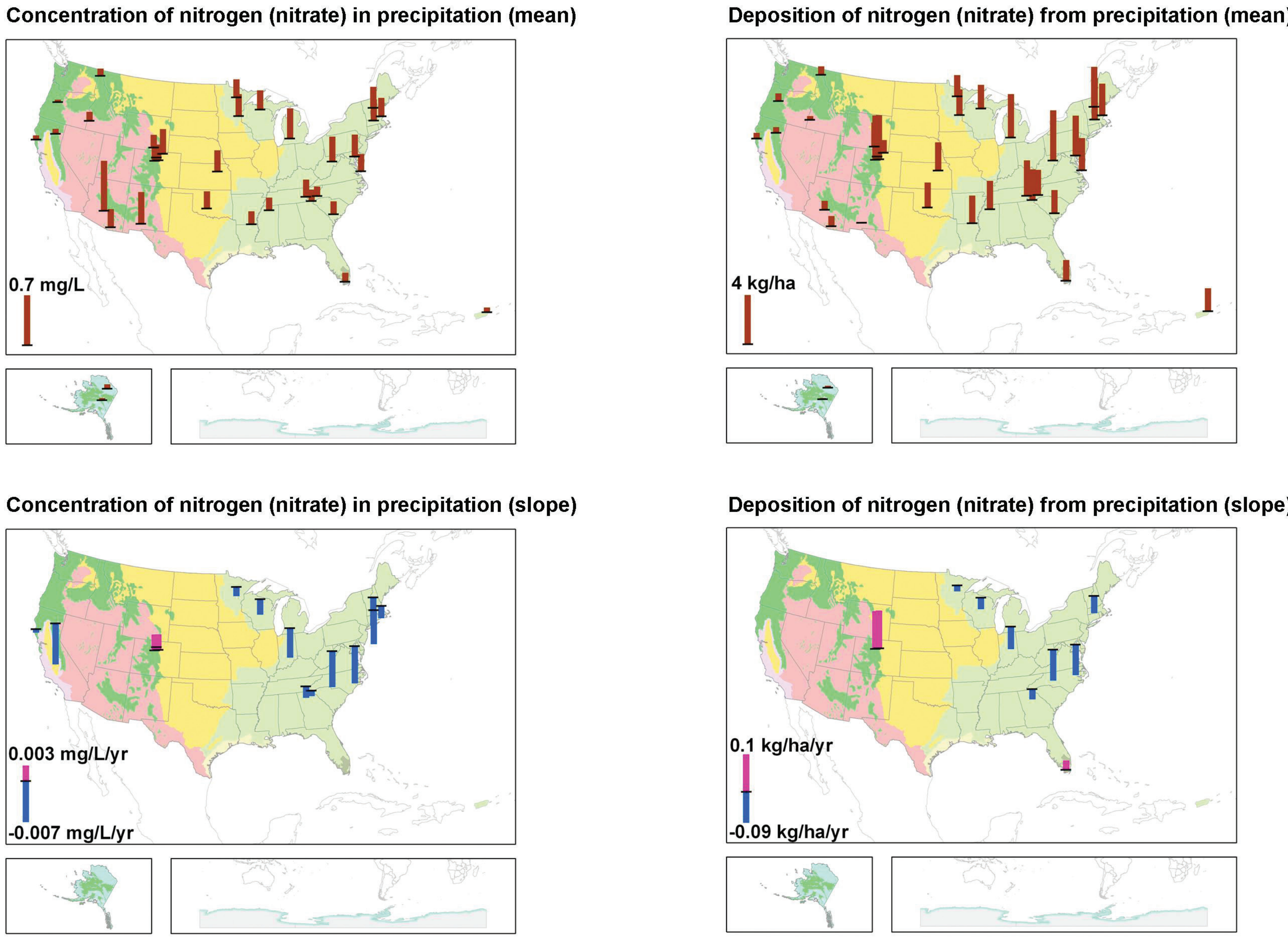


Figure 12-1. Continental patterns in nitrogen (nitrate) from precipitation: concentration (volume-weighted concentration, mg/L) and wet deposition (kg/ha). Top panels: long-term averages where positive values are red and negative values are green. Bottom panels: slopes of significant regression lines ($p < 0.05$) 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.

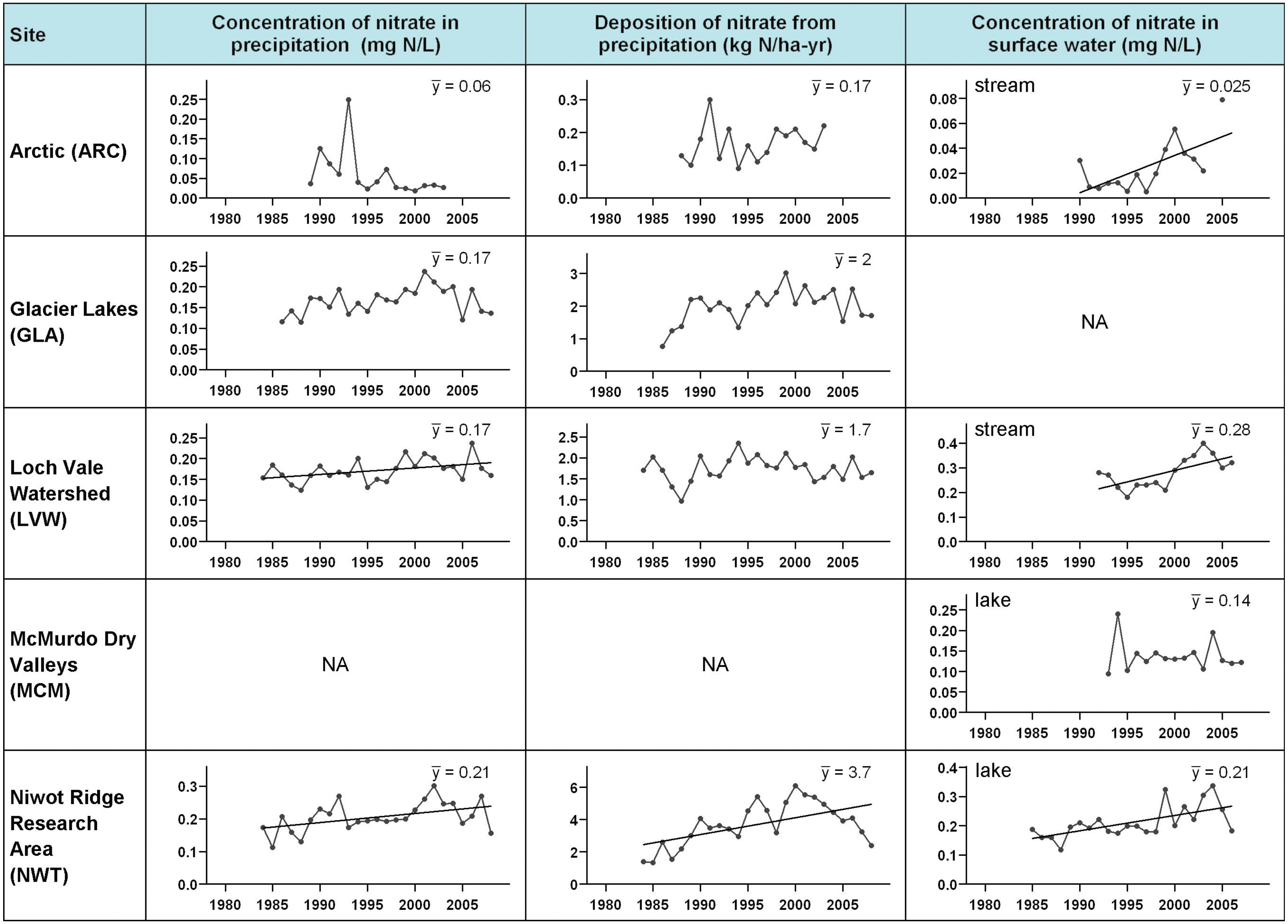


Figure 12-2. Trends for each alpine and arctic site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, 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.

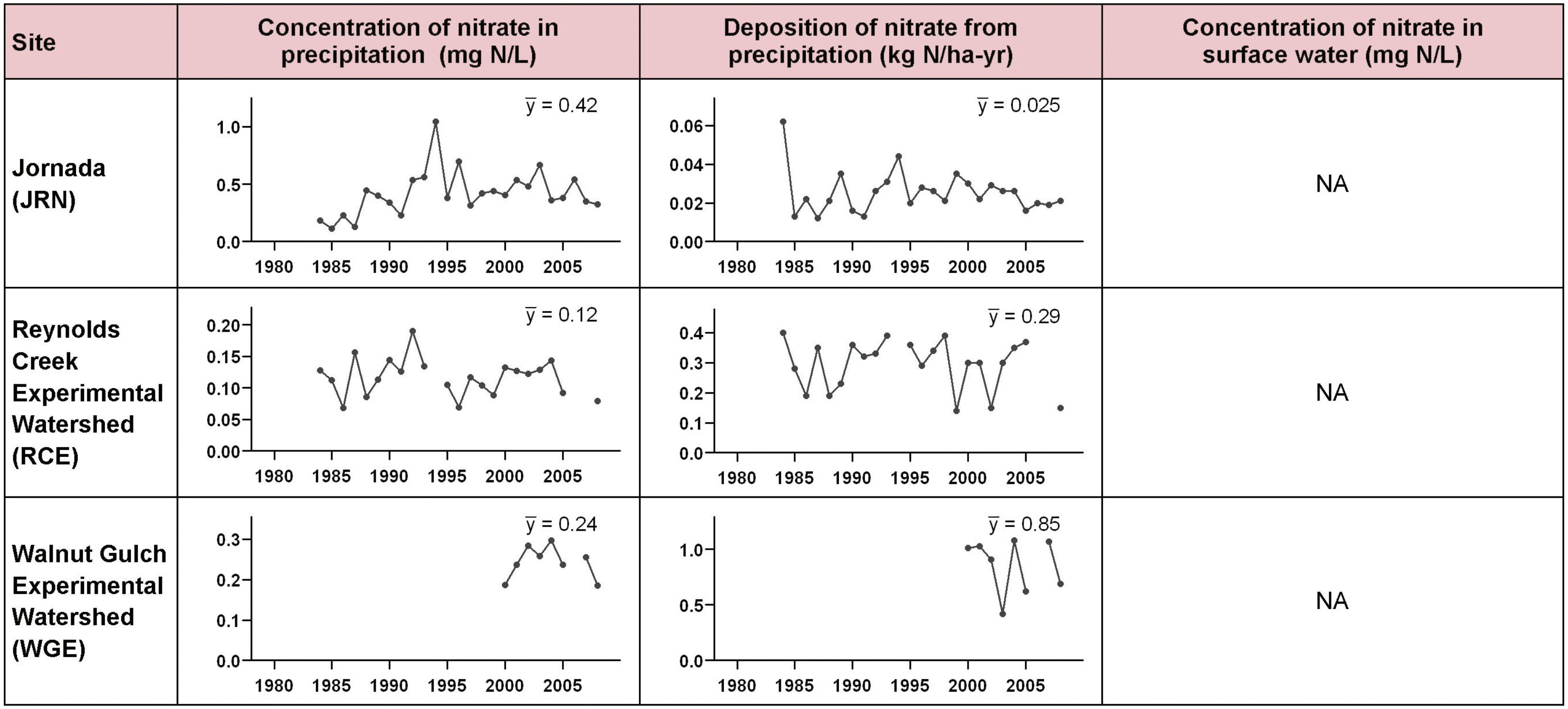


Figure 12-3. Trends for each aridland site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, 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.

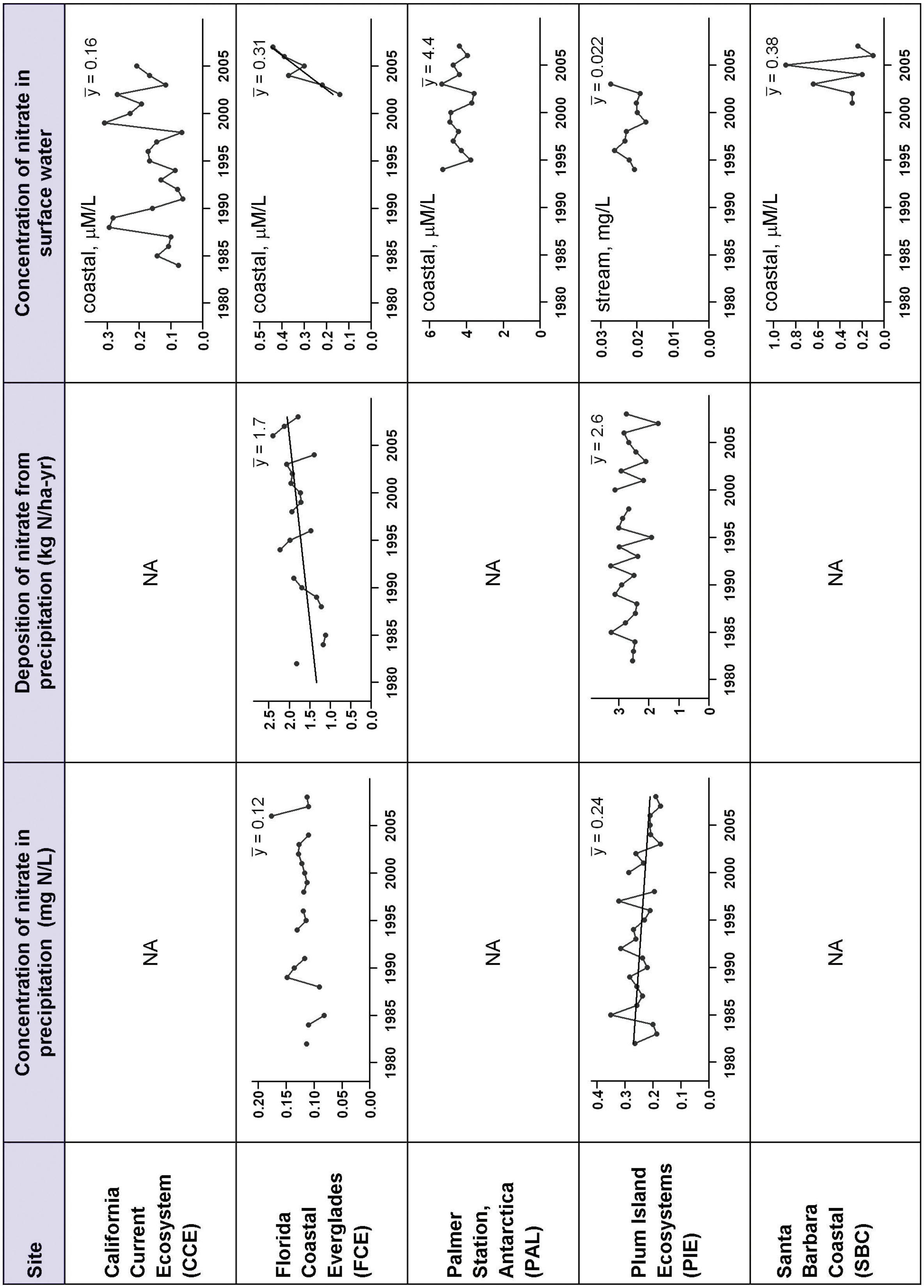


Figure 12-4 (coastal sites) continued next page.

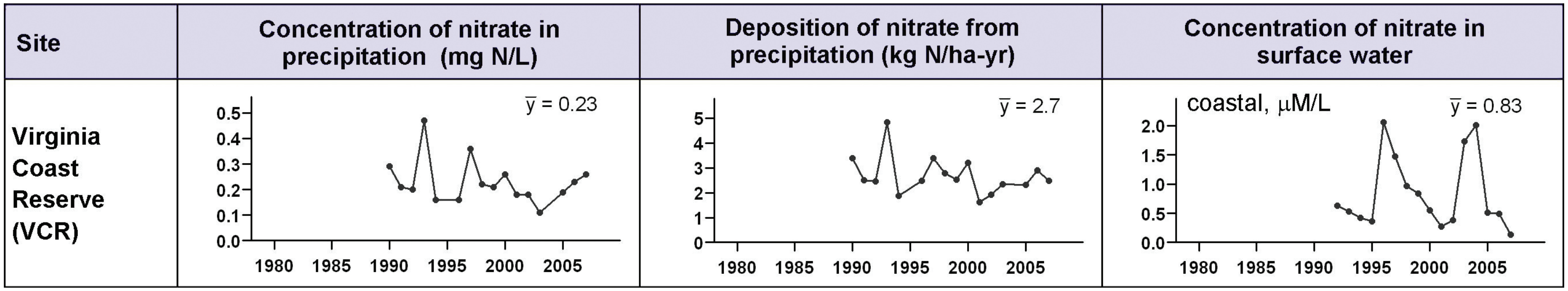


Figure 12-4. Trends for each coastal site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, 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.

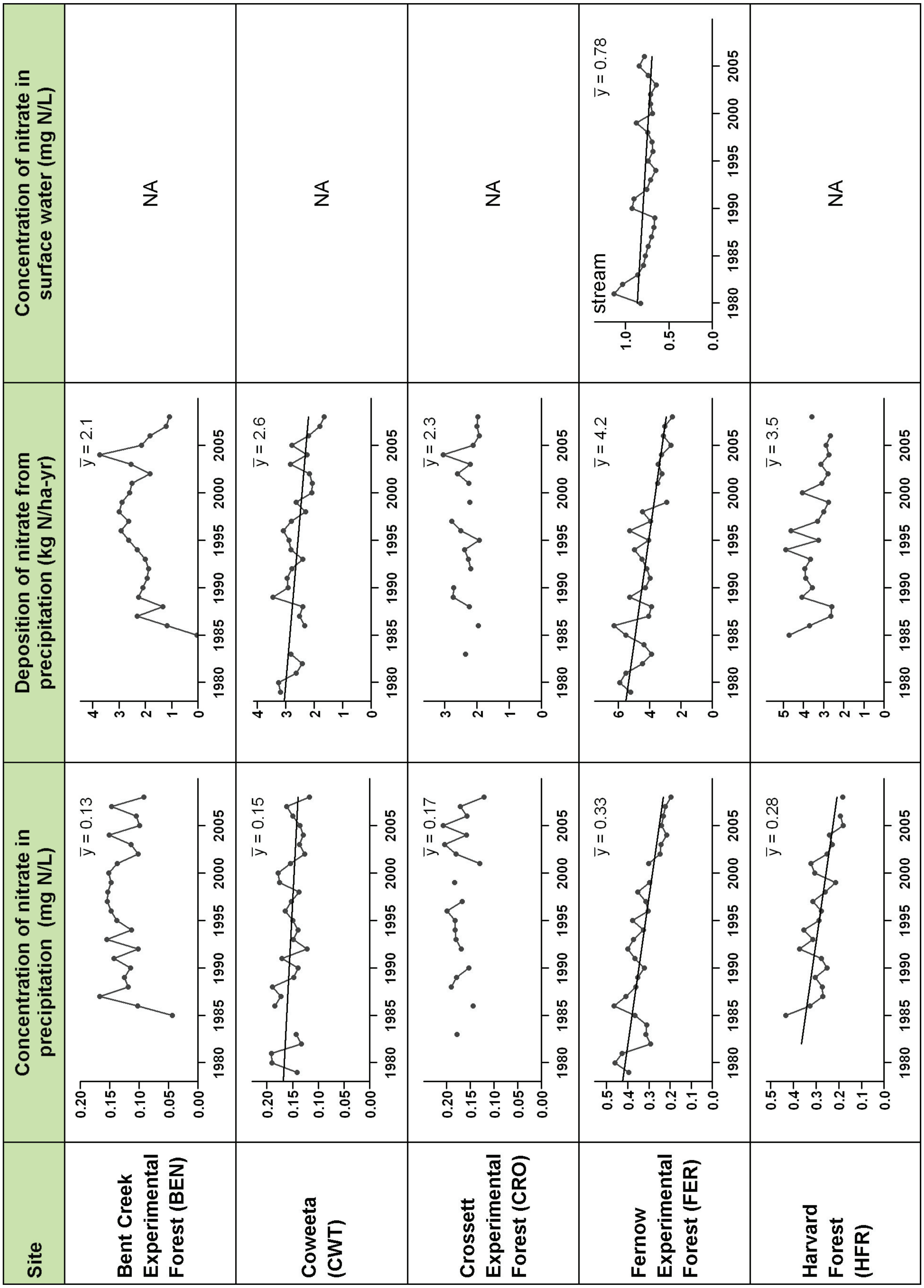


Figure 12-5 (eastern forest sites) continued next page.

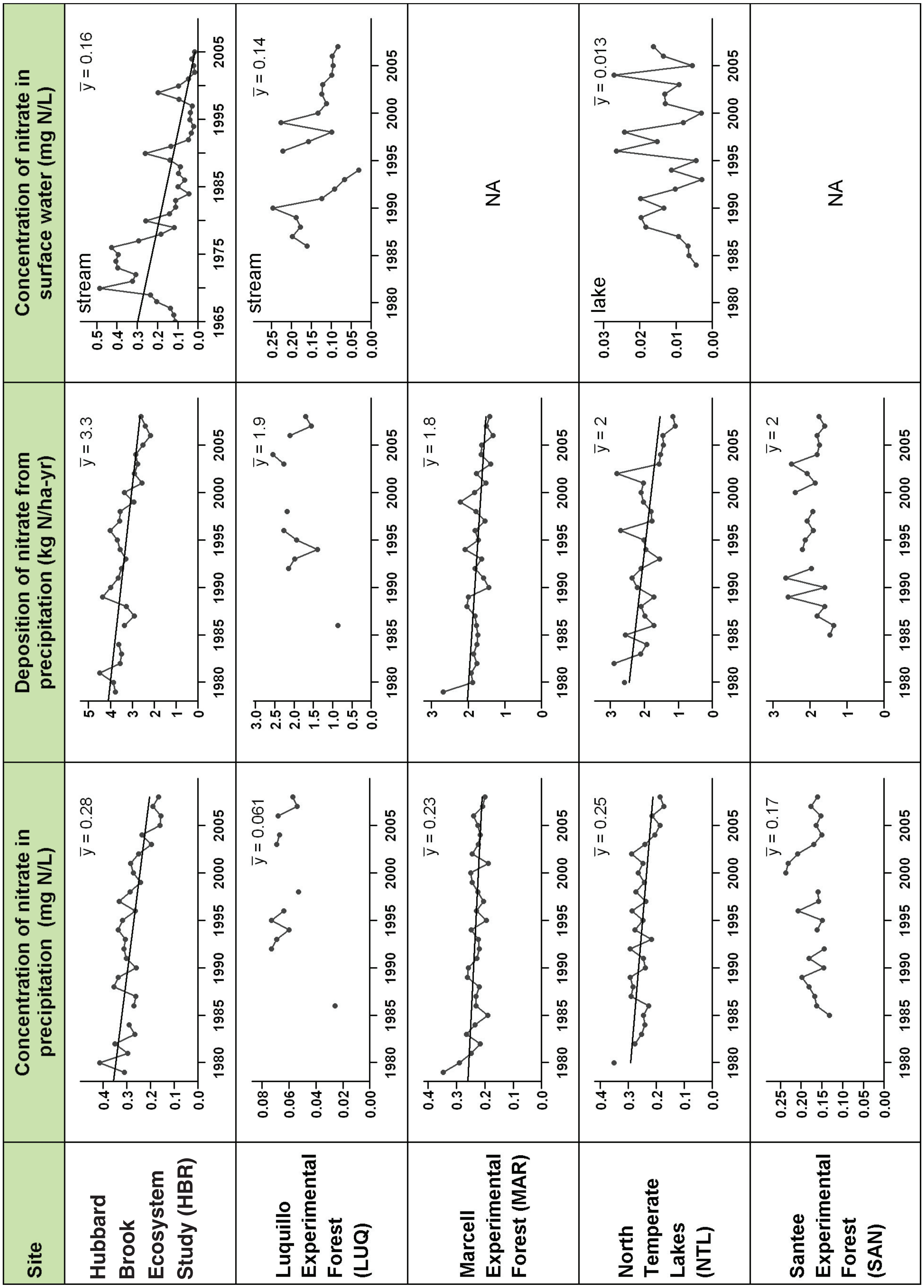


Figure 12-5 (eastern forest sites) continued next page.

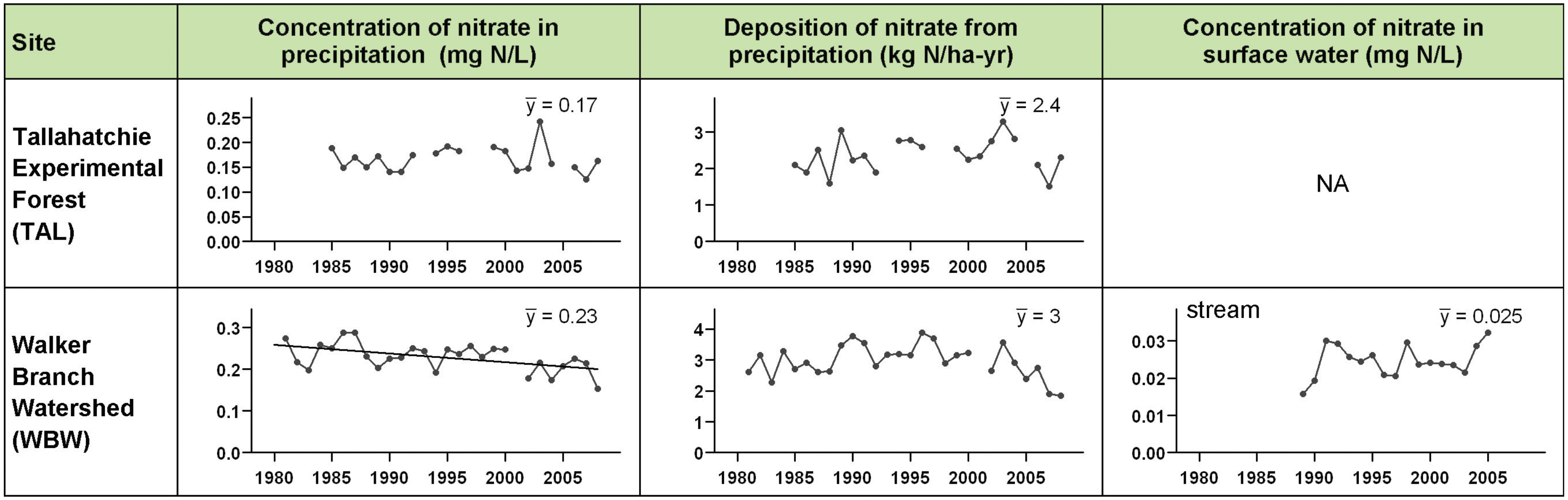


Figure 12-5. Trends for each eastern forest site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, 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.

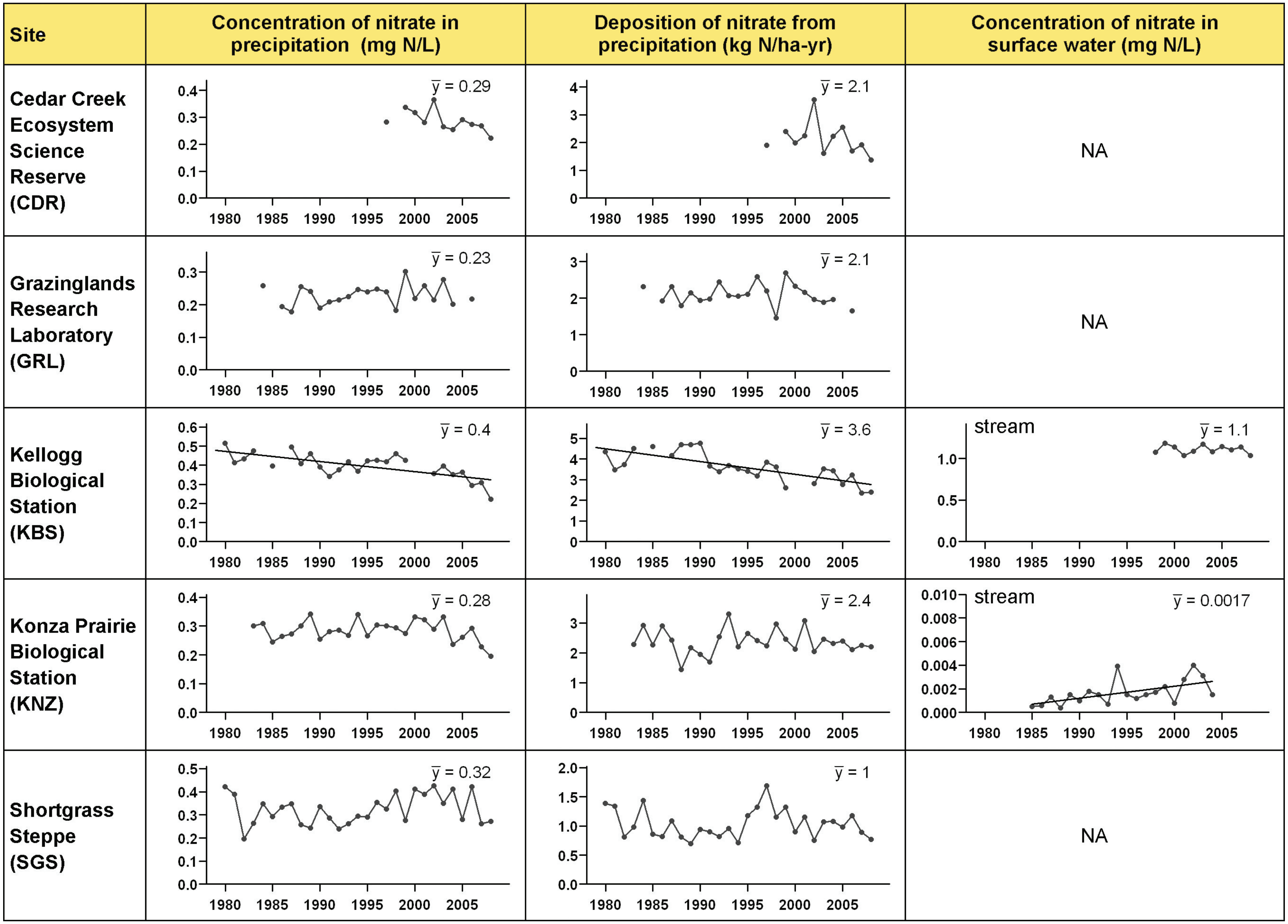


Figure 12-6. Trends for each temperate grassland and savanna site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and 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.

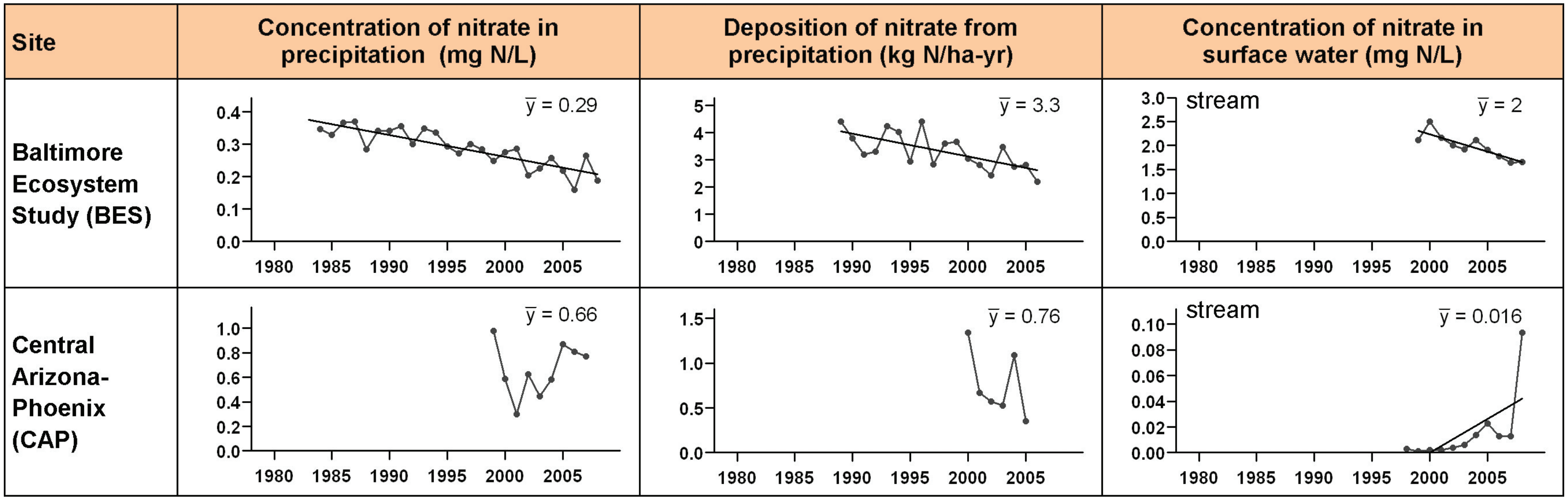


Figure 12-7. Trends for each urban site: nitrate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, 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.

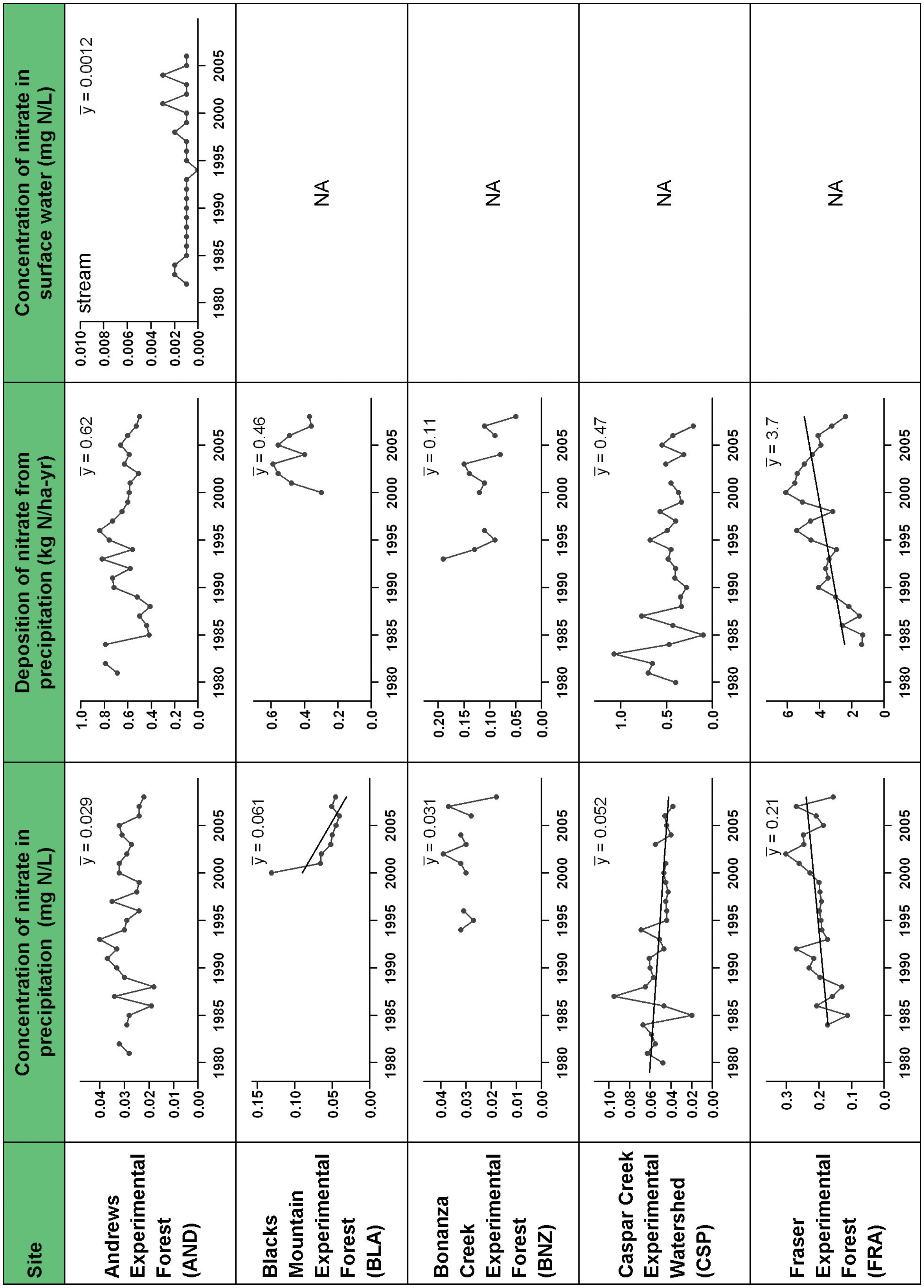


Figure 12-8 (western forest sites) continued next page.

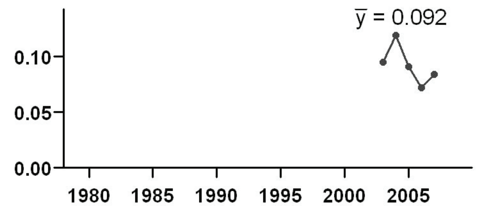
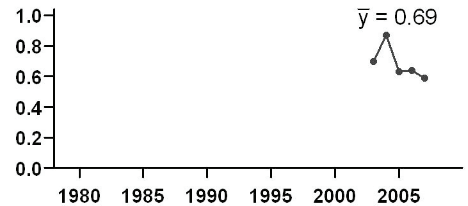
Site	Concentration of nitrate in precipitation (mg N/L)	Deposition of nitrate from precipitation (kg N/ha-yr)	Concentration of nitrate in surface water (mg N/L)
Priest River Experimental Forest (PRI)			NA

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.

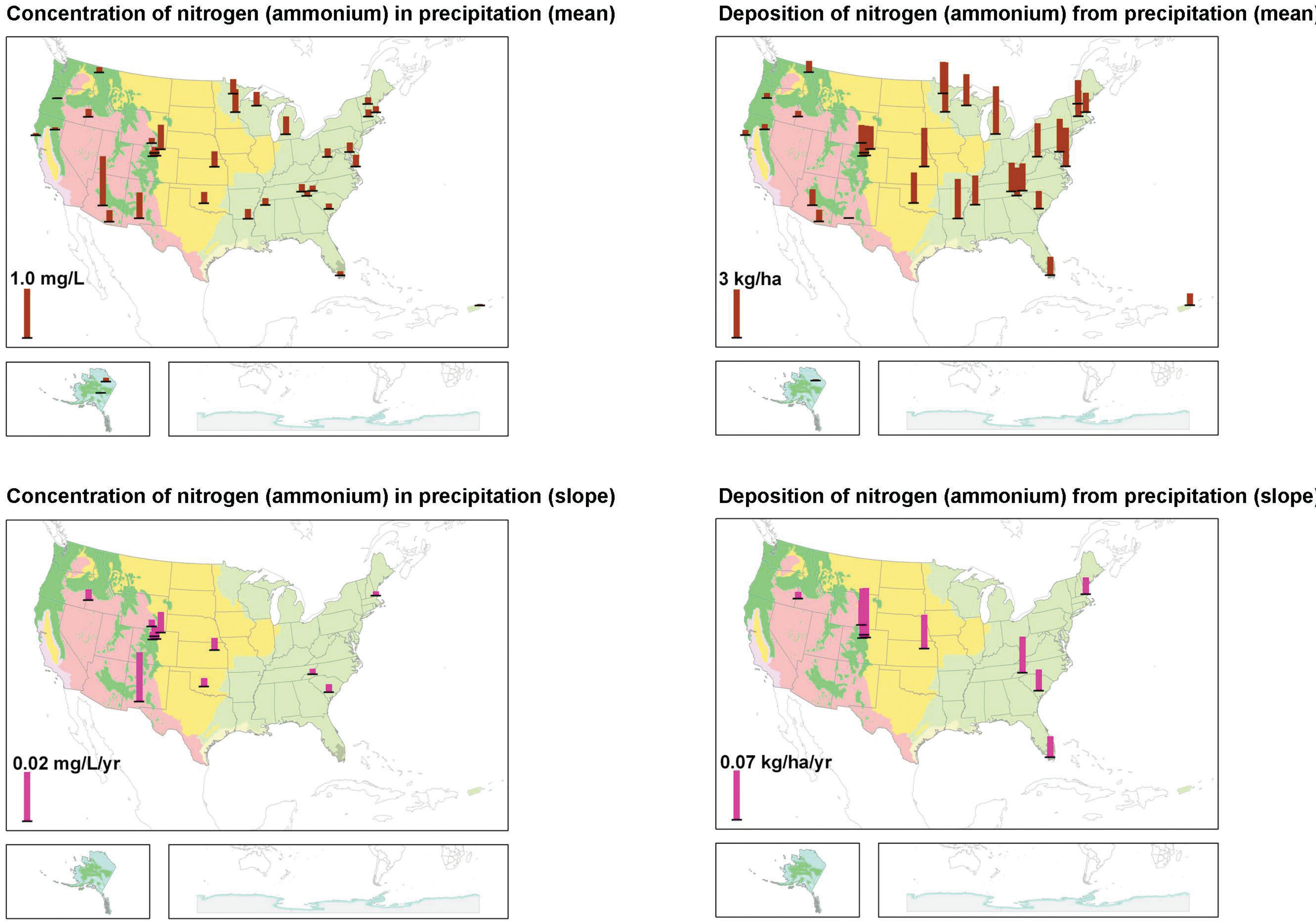


Figure 12-9. Continental patterns in nitrogen (ammonium) from precipitation: concentration (volume-weighted concentration, mg/L) and wet deposition (kg/ha). Top panels: long-term averages where positive values are red and negative values are green. Bottom panels: slopes of significant regression lines ($p < 0.05$) 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.

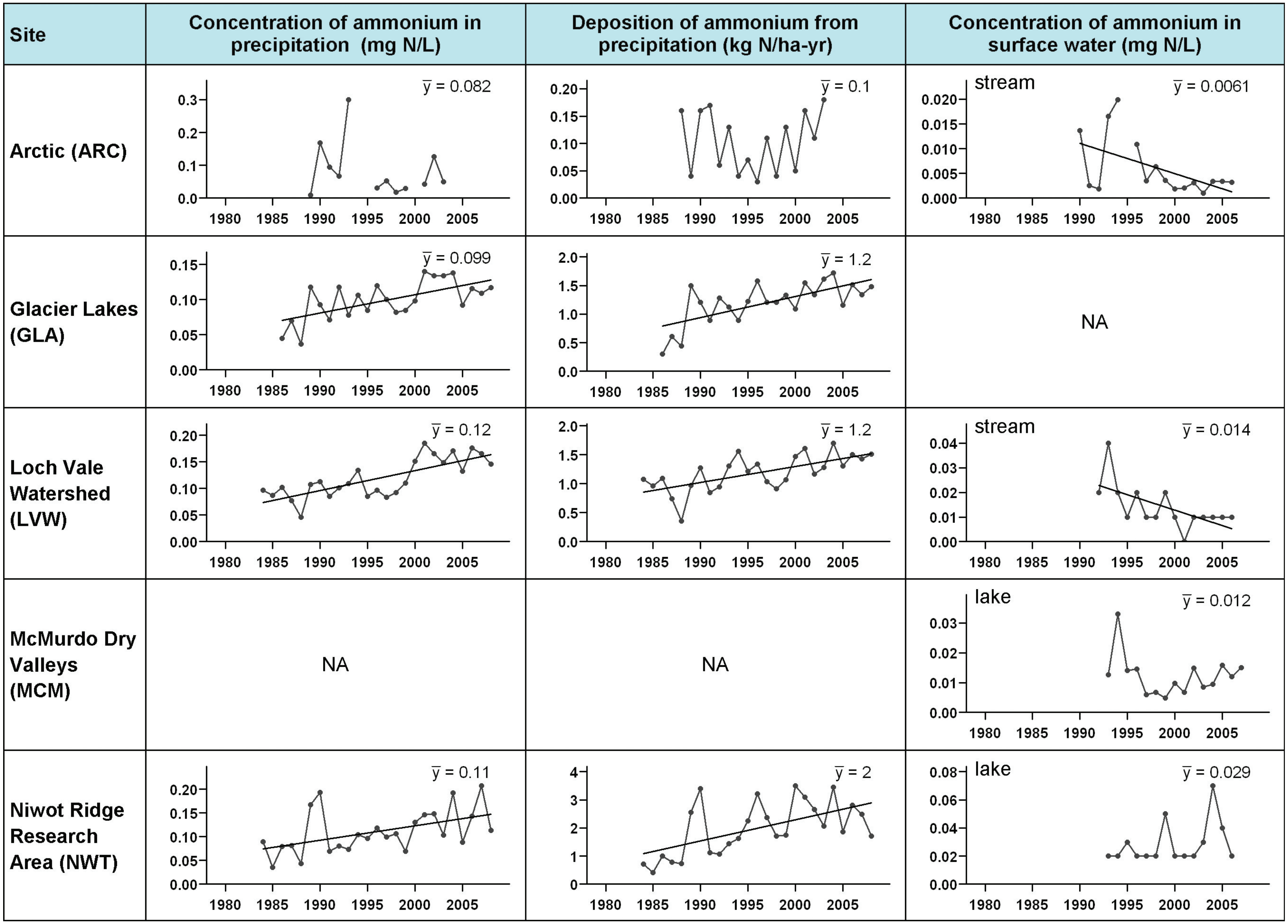


Figure 12-10. Trends for each alpine and arctic site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, 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.

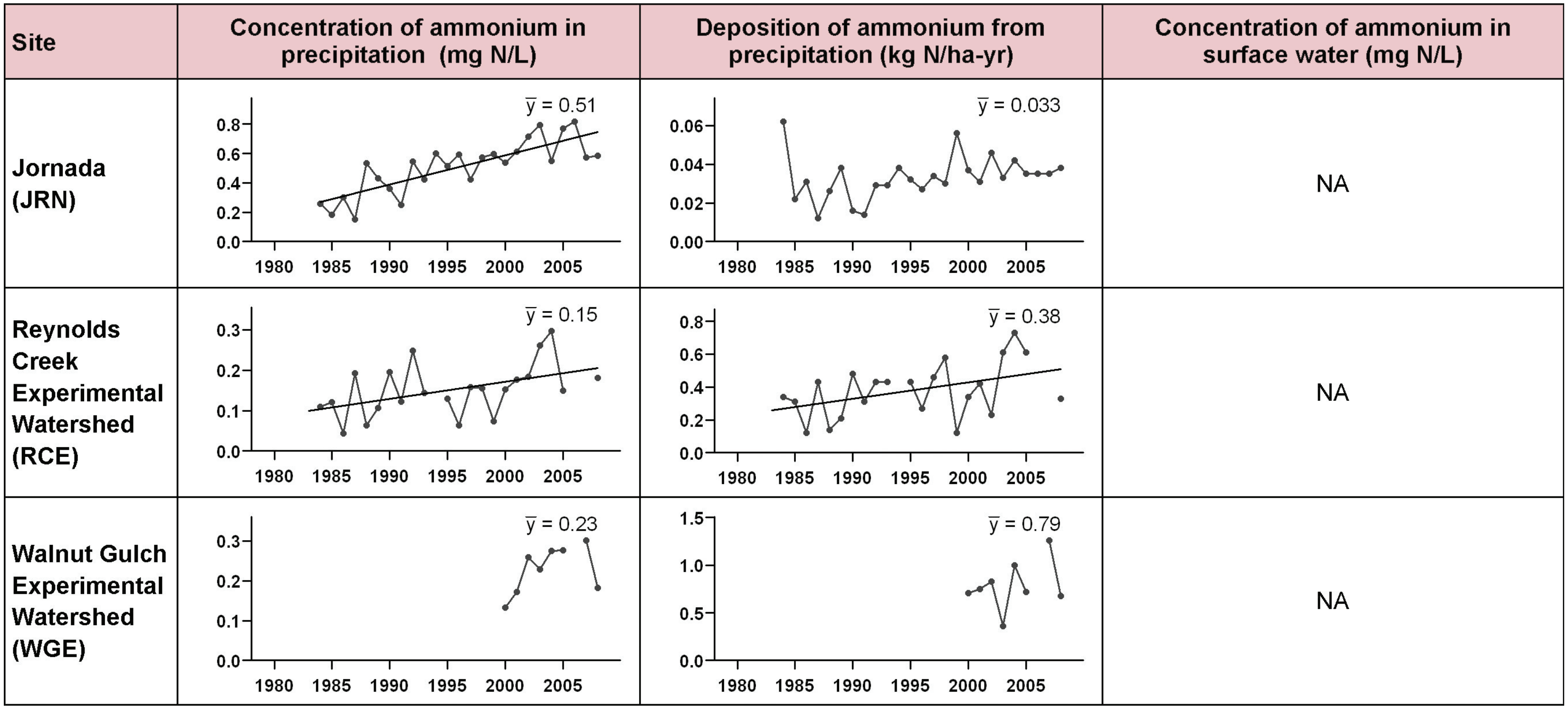


Figure 12-11. Trends for each aridland site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, 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.

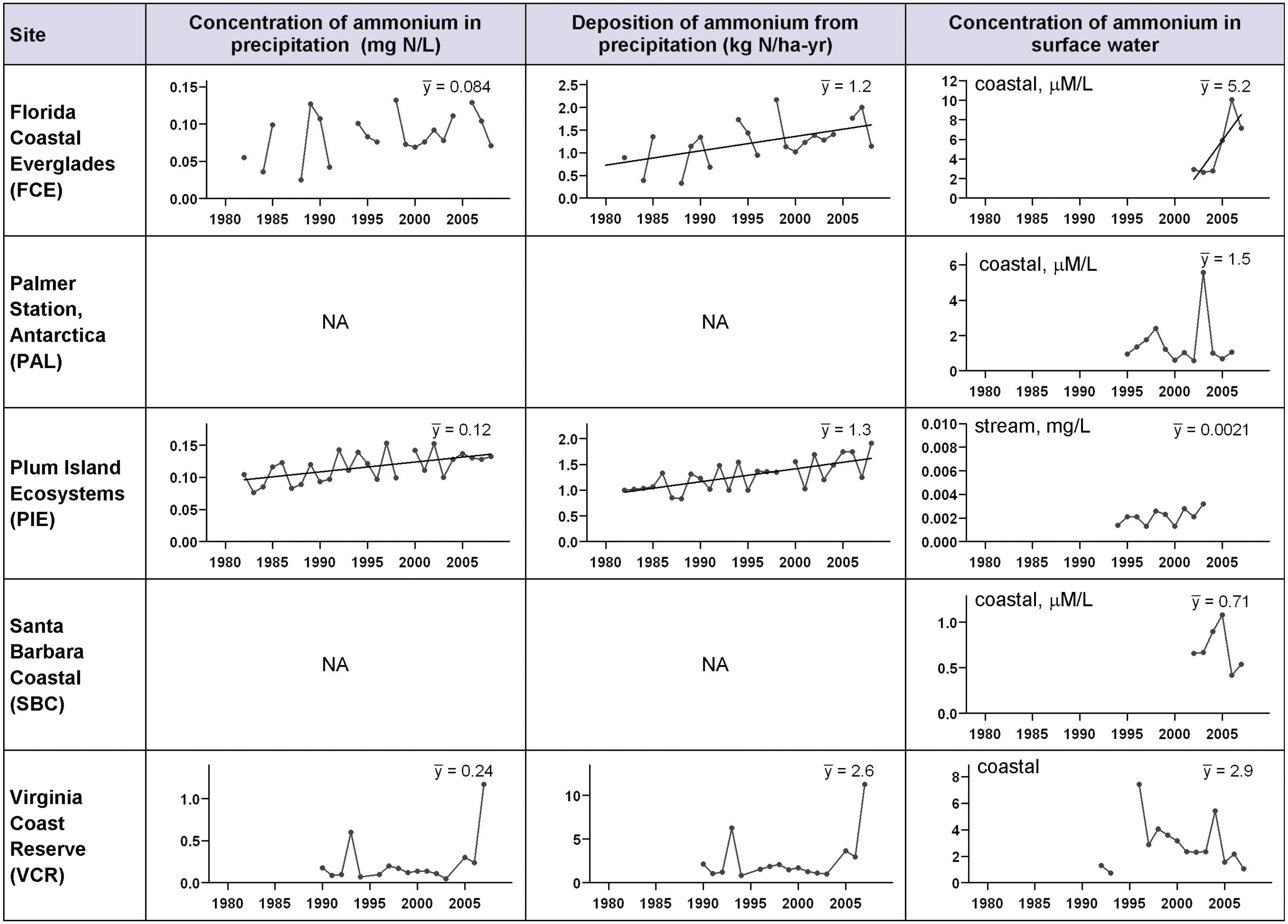


Figure 12-12. Trends for each coastal site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, 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.

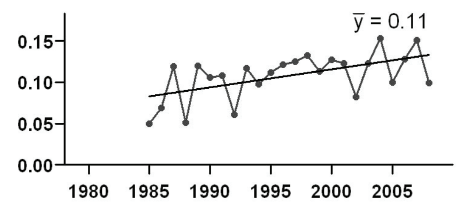
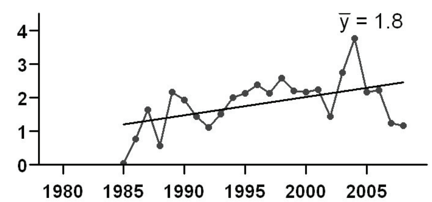
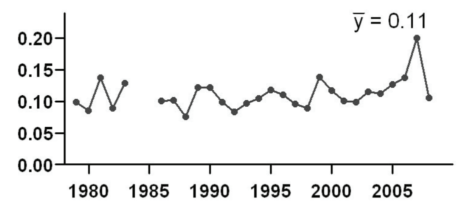
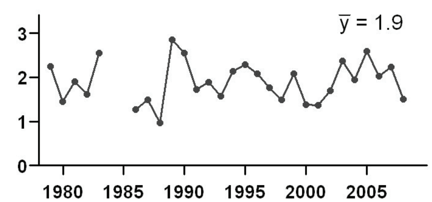
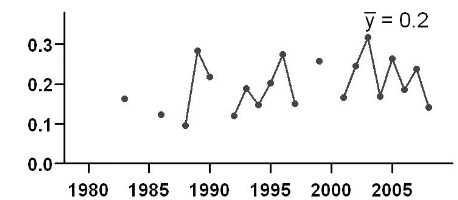
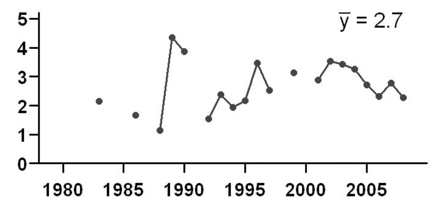
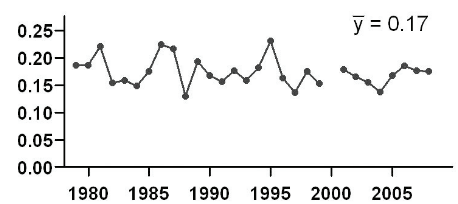
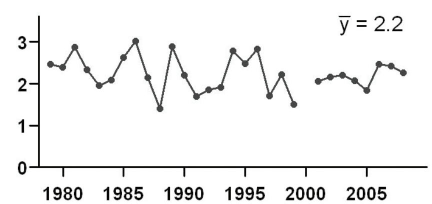
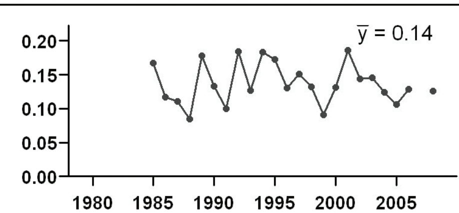
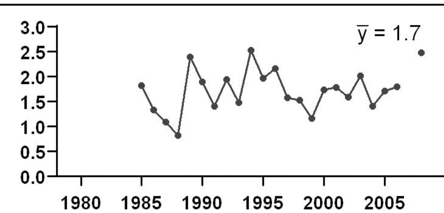
Site	Concentration of ammonium in precipitation (mg N/L)	Deposition of ammonium from precipitation (kg N/ha-yr)	Concentration of ammonium in surface water (mg N/L)
Bent Creek Experimental Forest (BEN)			NA
Coweeta (CWT)			NA
Crossett Experimental Forest (CRO)			NA
Fernow Experimental Forest (FER)			NA
Harvard Forest (HFR)			NA

Figure 12-13 (eastern forest sites) continued next page.

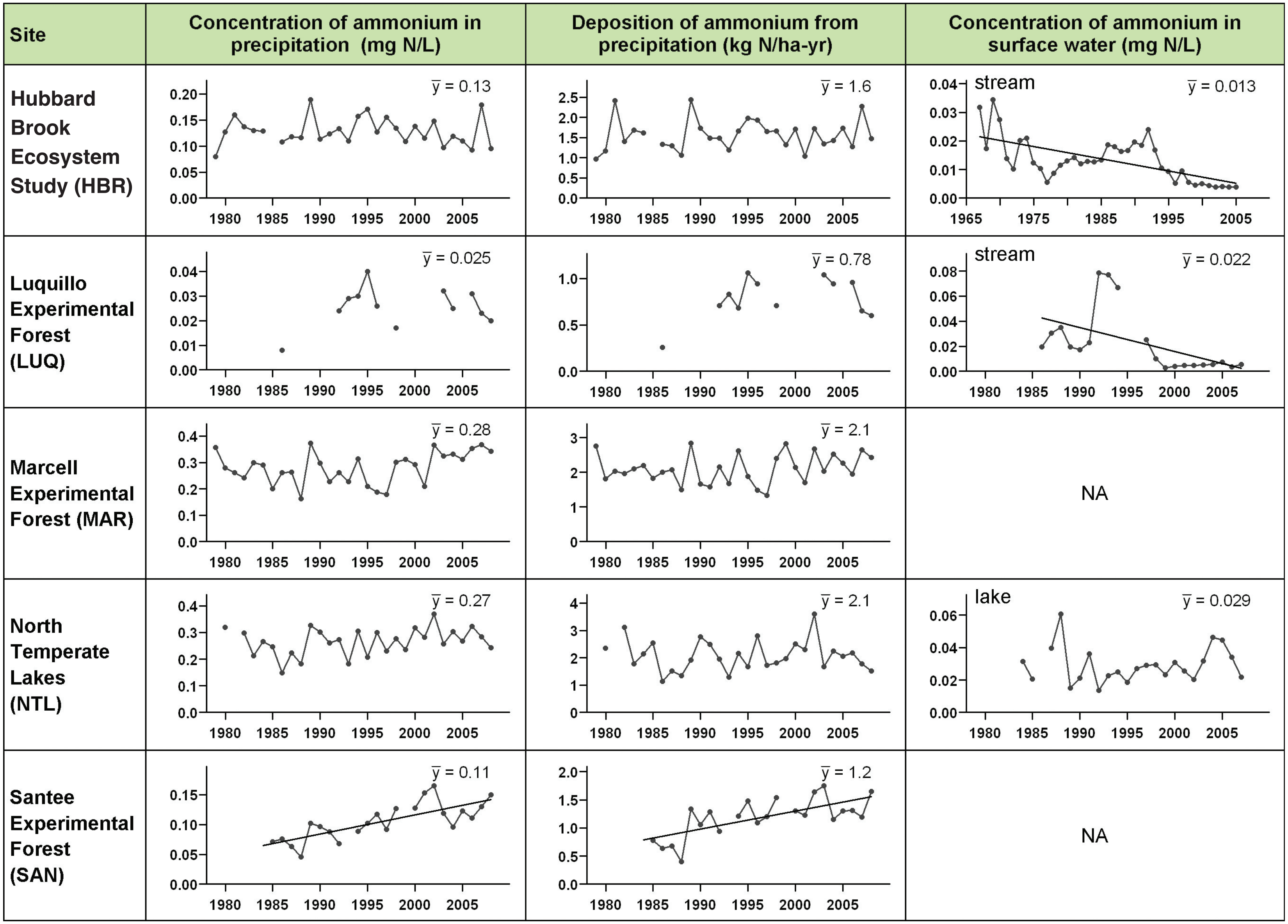


Figure 12-13 (eastern forest sites) continued next page.

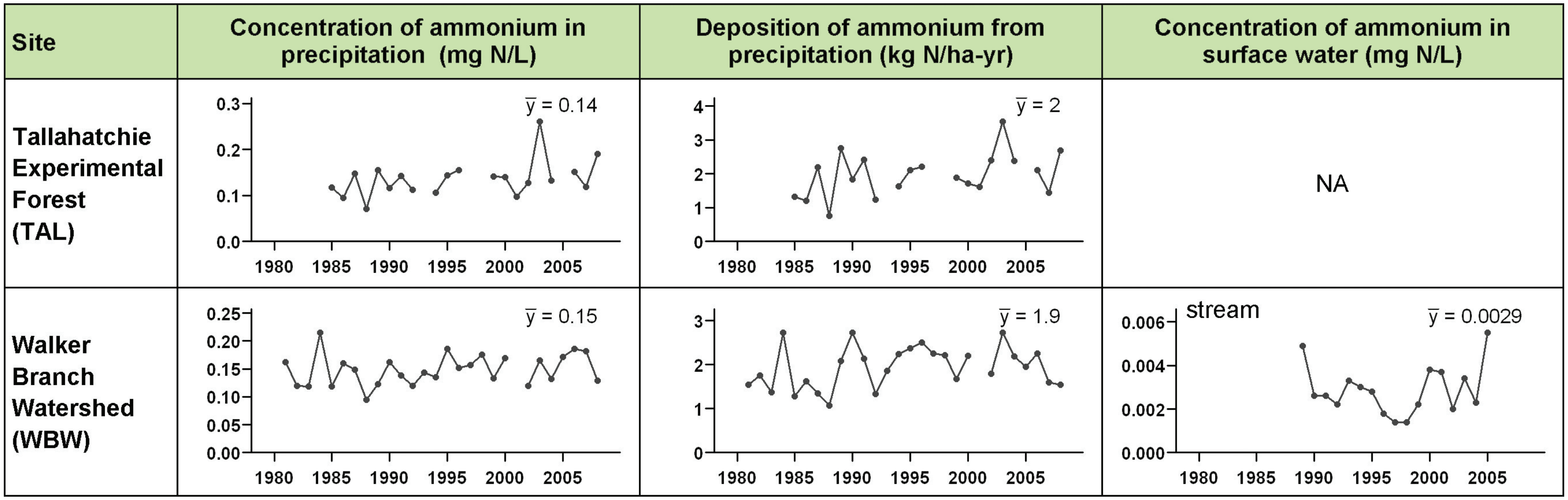


Figure 12-13. Trends for each eastern forest site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, 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.

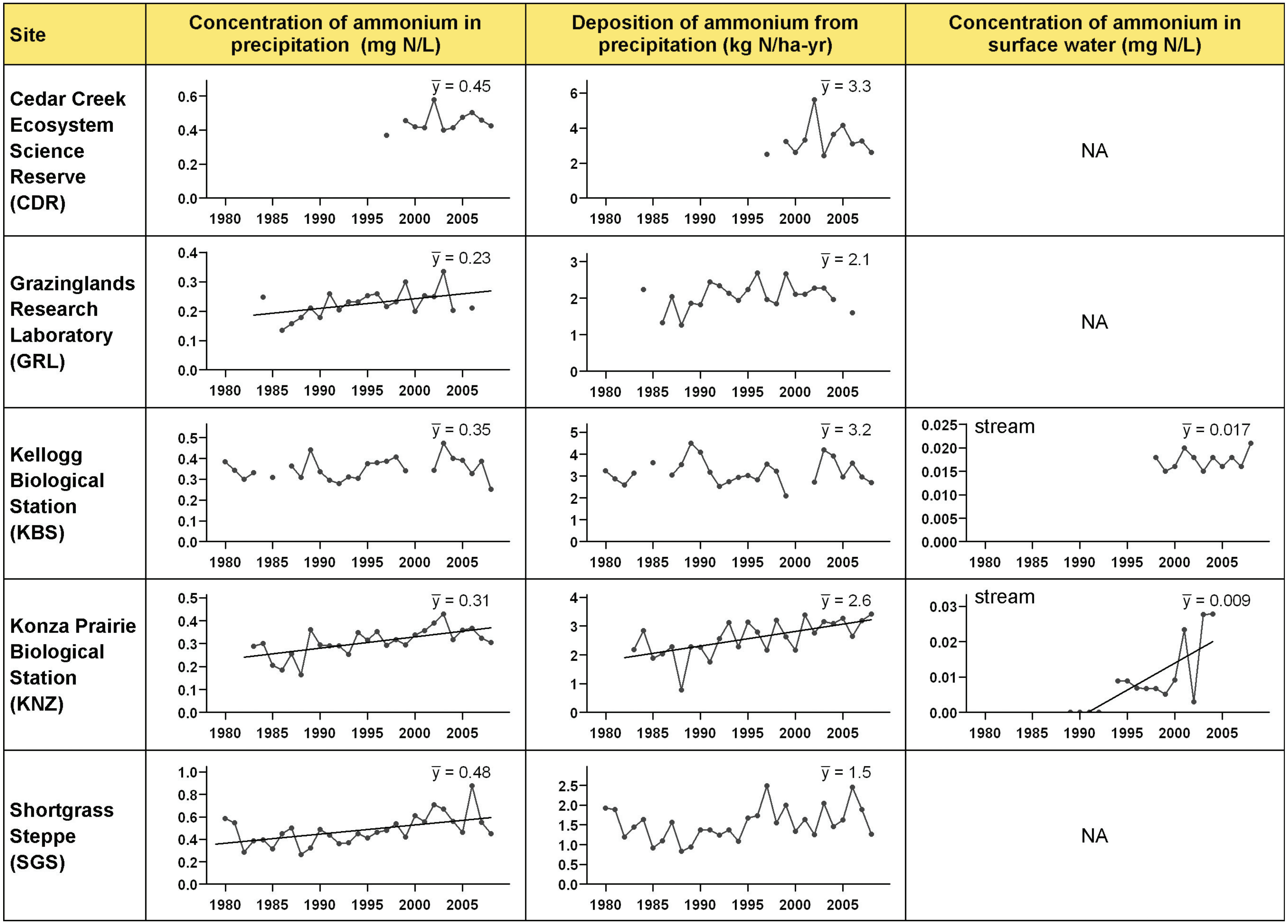


Figure 12-14. Trends for each temperate grassland and savanna site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, 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.

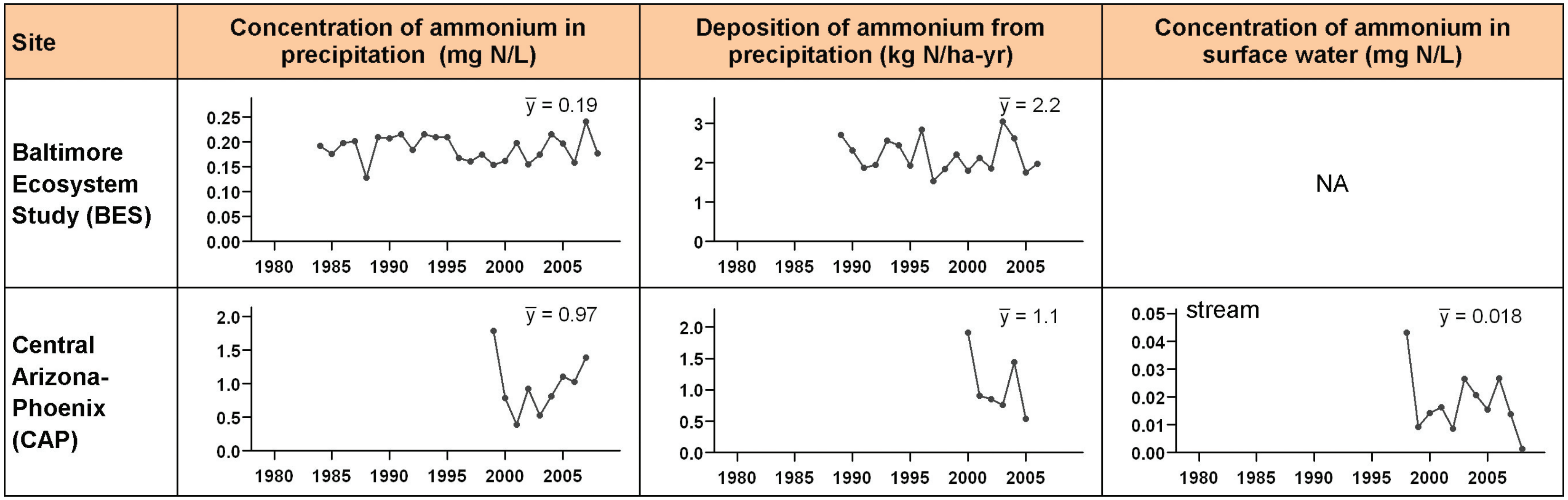


Figure 12-15. Trends for each urban site: ammonium concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, 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.

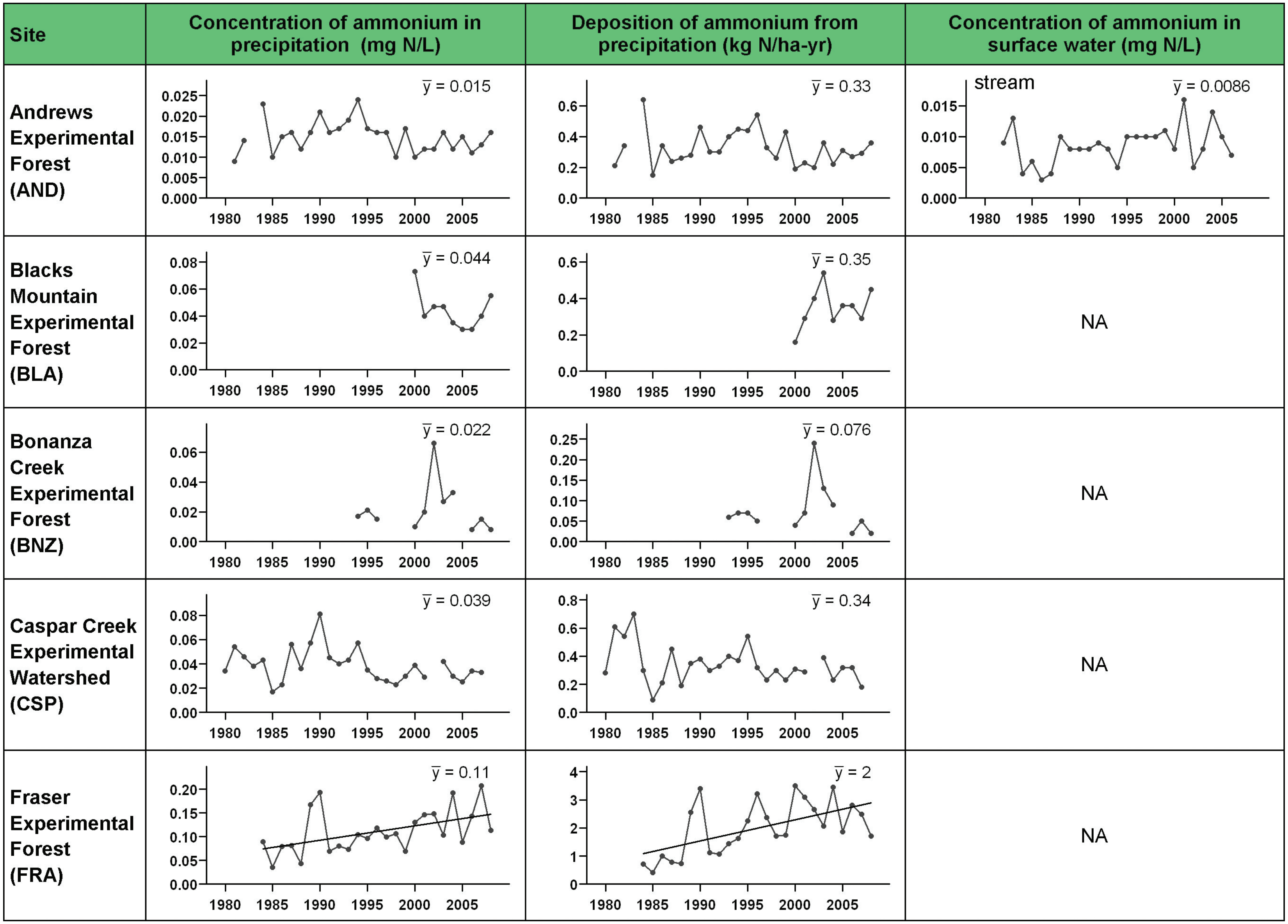


Figure 12-16 (western forest sites) continued next page.

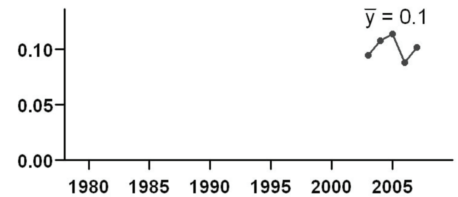
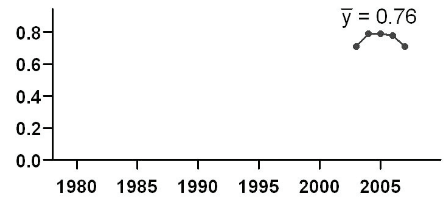
Site	Concentration of ammonium in precipitation (mg N/L)	Deposition of ammonium from precipitation (kg N/ha-yr)	Concentration of ammonium in surface water (mg N/L)
Priest River Experimental Forest (PRI)			NA

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.

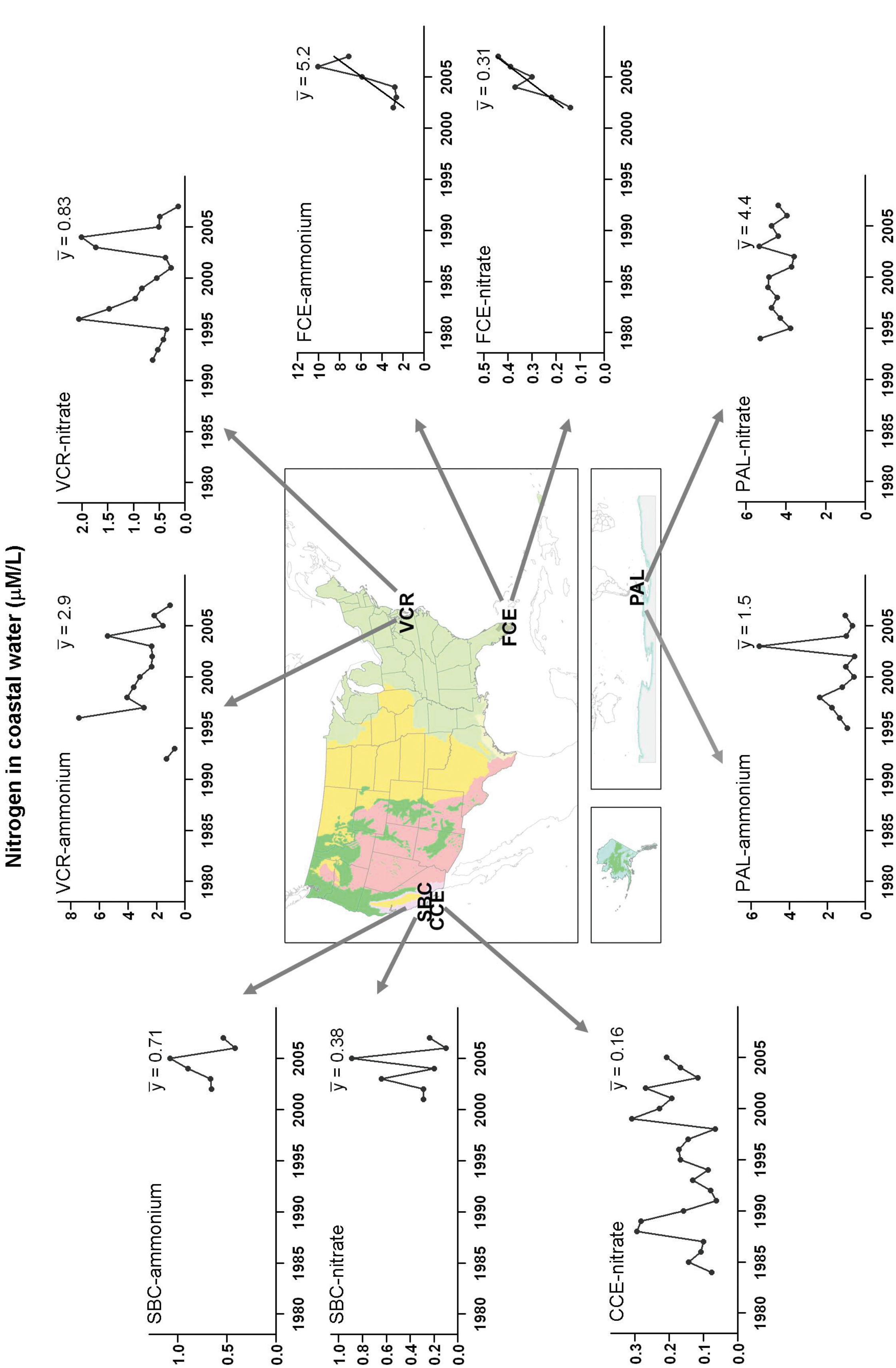


Figure 12-17. Concentration of nitrogen (ammonium and nitrate, µM/L) in coastal water through time at five sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Florida Coastal Everglades (FCE) (1.32 ammonium and 0.06 nitrate).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

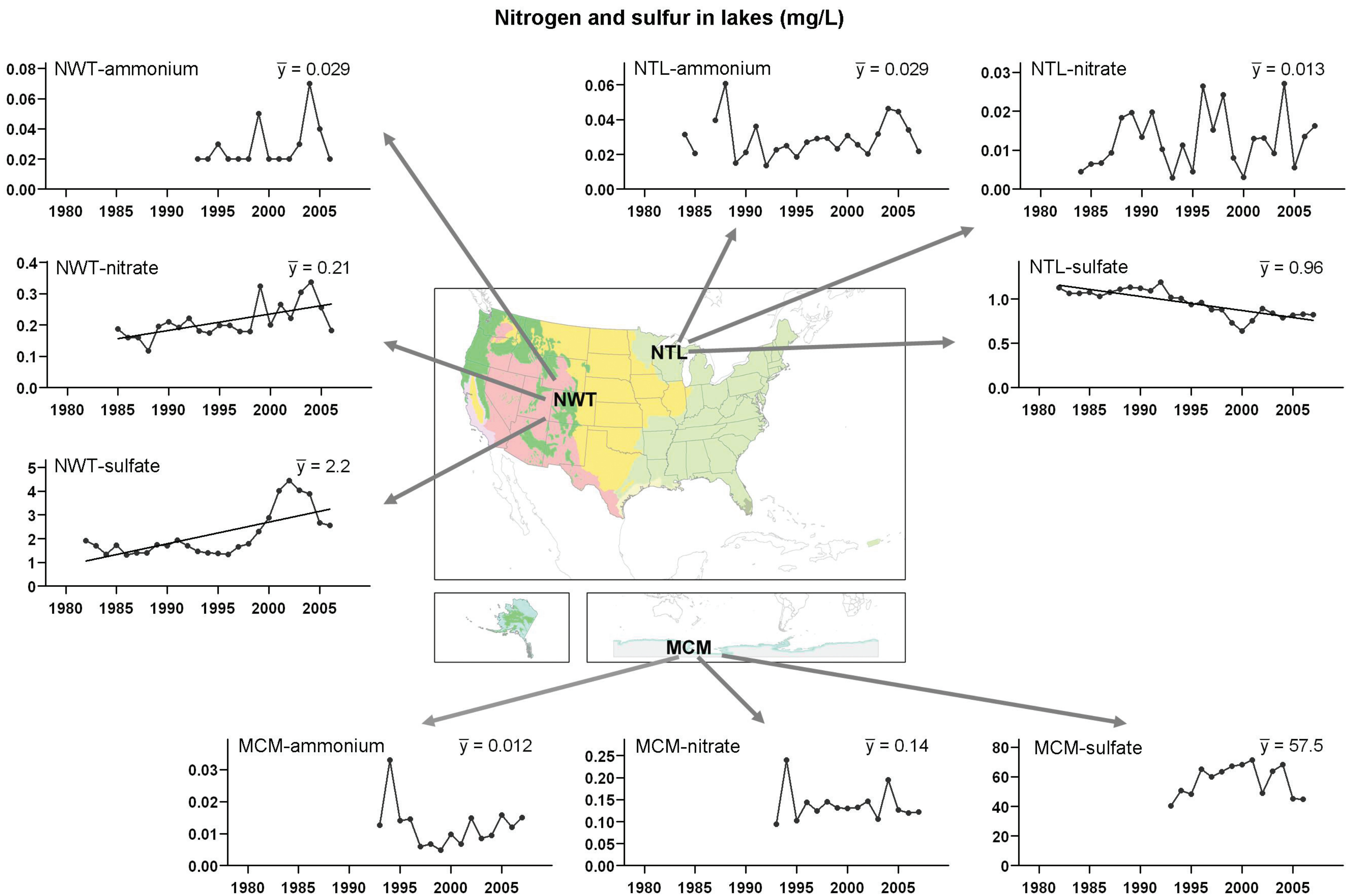


Figure 12-18. Concentrations of nitrogen (ammonium and nitrate, mg/L) and sulfur (sulfate, mg/L) in lakes through time at three sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Niwot Ridge Research Area (NWT) (0.005 nitrate, 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.

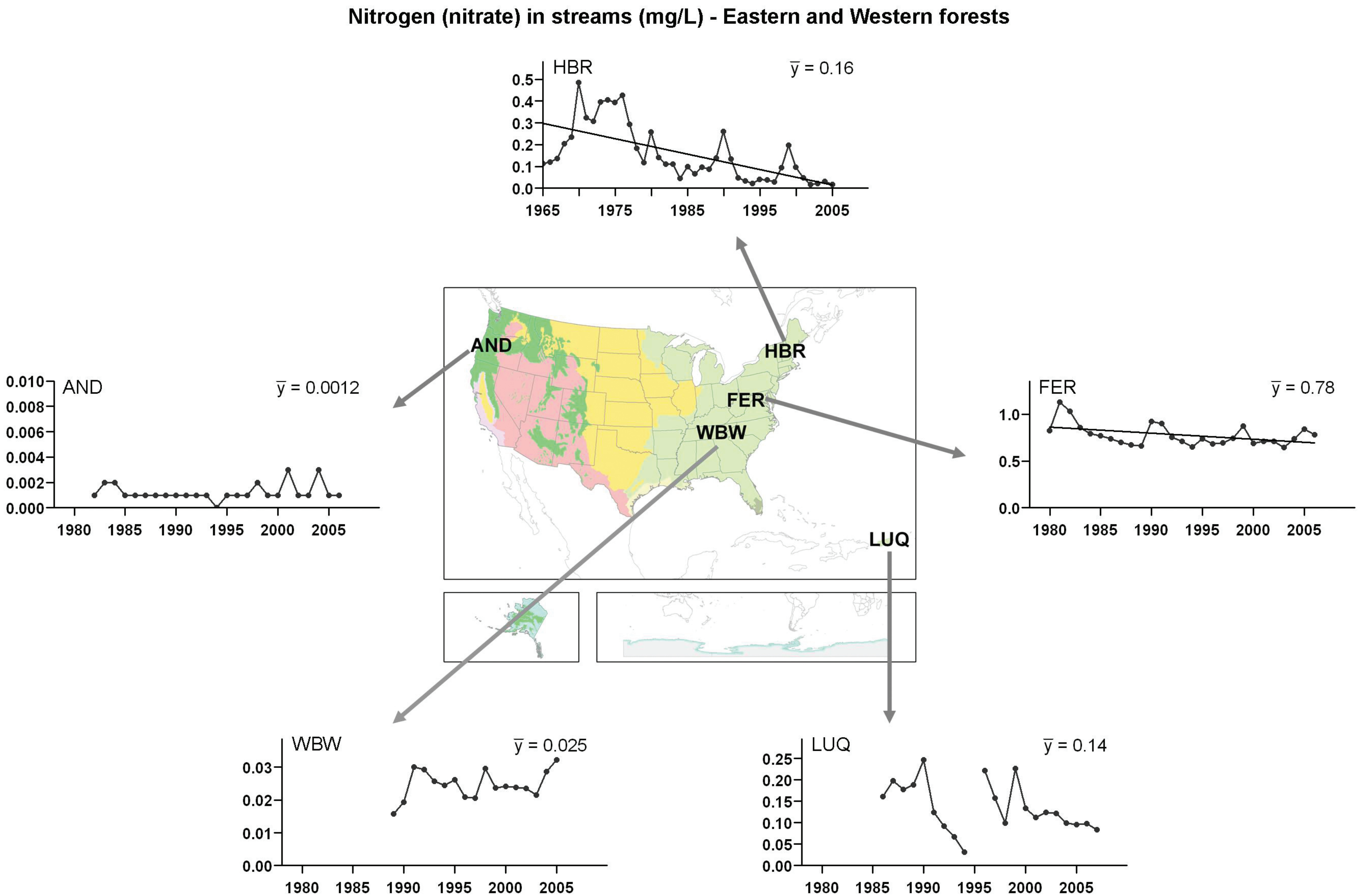


Figure 12-19. Concentration of nitrogen (nitrate, mg/L) in streams through time at four eastern forest sites and one western forest site. A simple line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Fernow Experimental Forest (FER) (-0.006) and Hubbard 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.

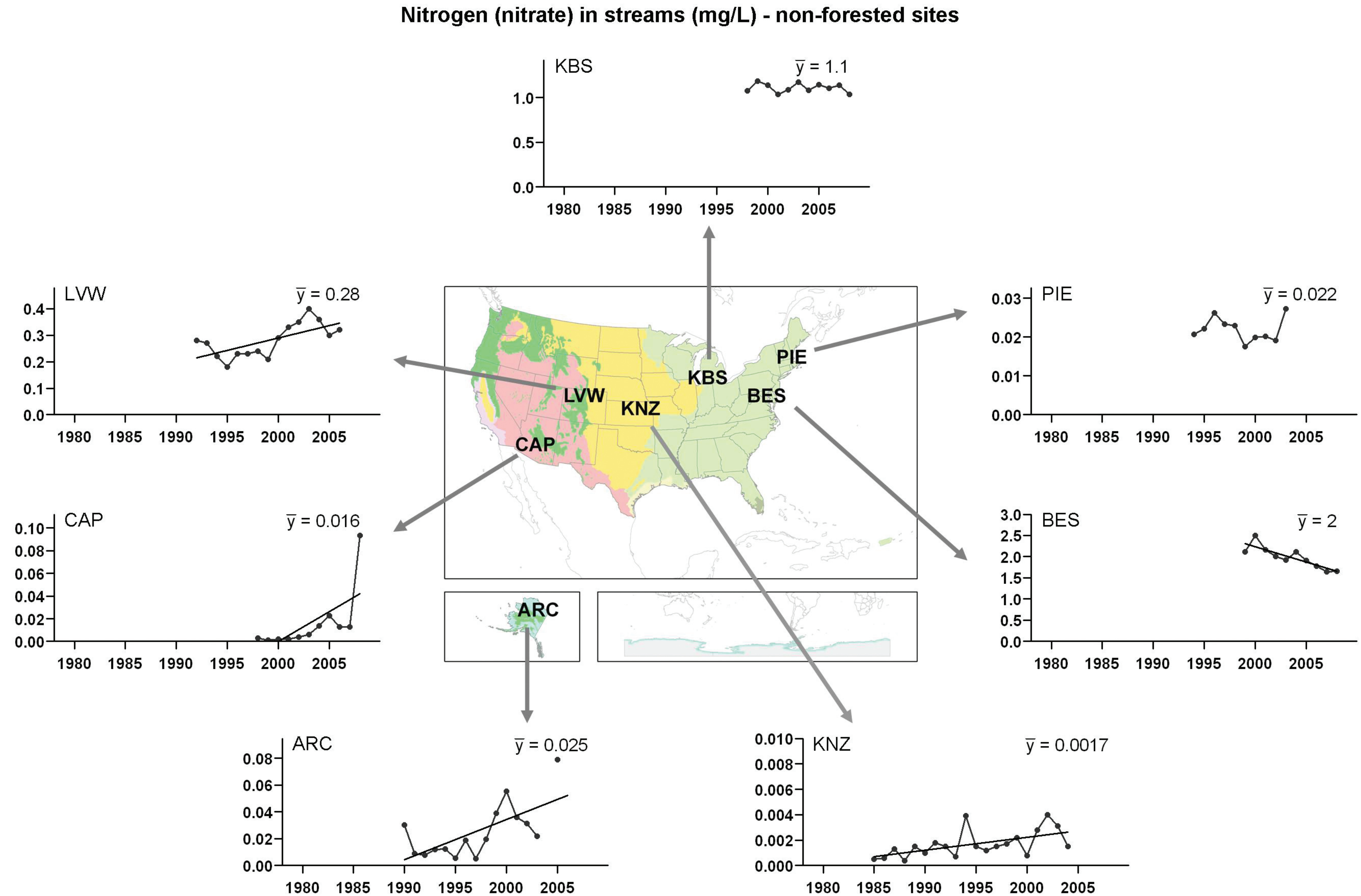


Figure 12-20. Concentration of nitrogen (nitrate, mg/L) in streams through time at seven nonforested sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Arctic (ARC) (0.0030), Baltimore Ecosystem Study (BES) (-0.0733), Central 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.

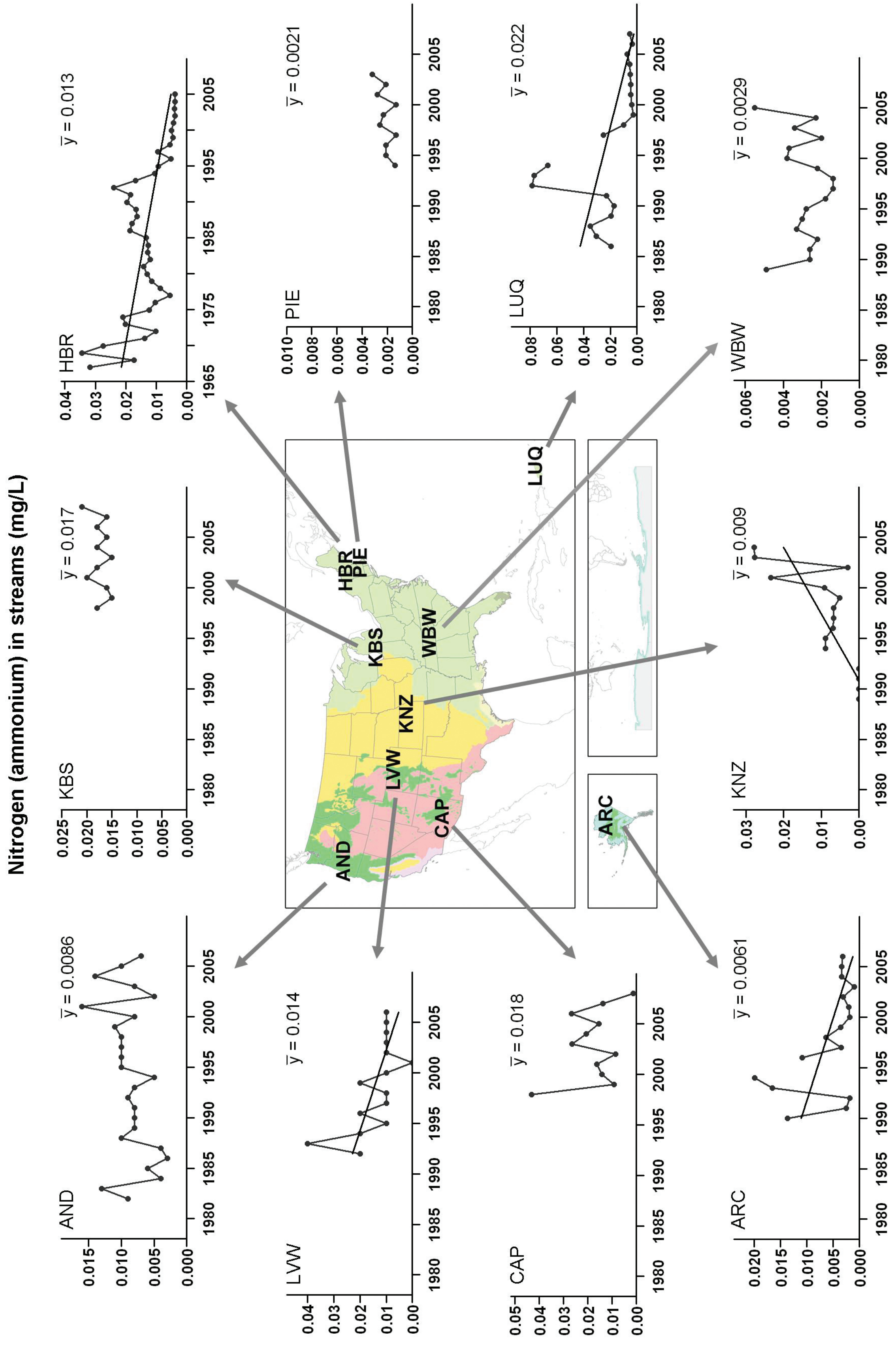


Figure 12-21. Concentration of nitrogen (ammonium, mg/L) in streams through time at ten sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Arctic (ARC) (-0.0006), Hubbard Brook Ecosystem Study (HBR) (-0.0004), Konza Prairie 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.

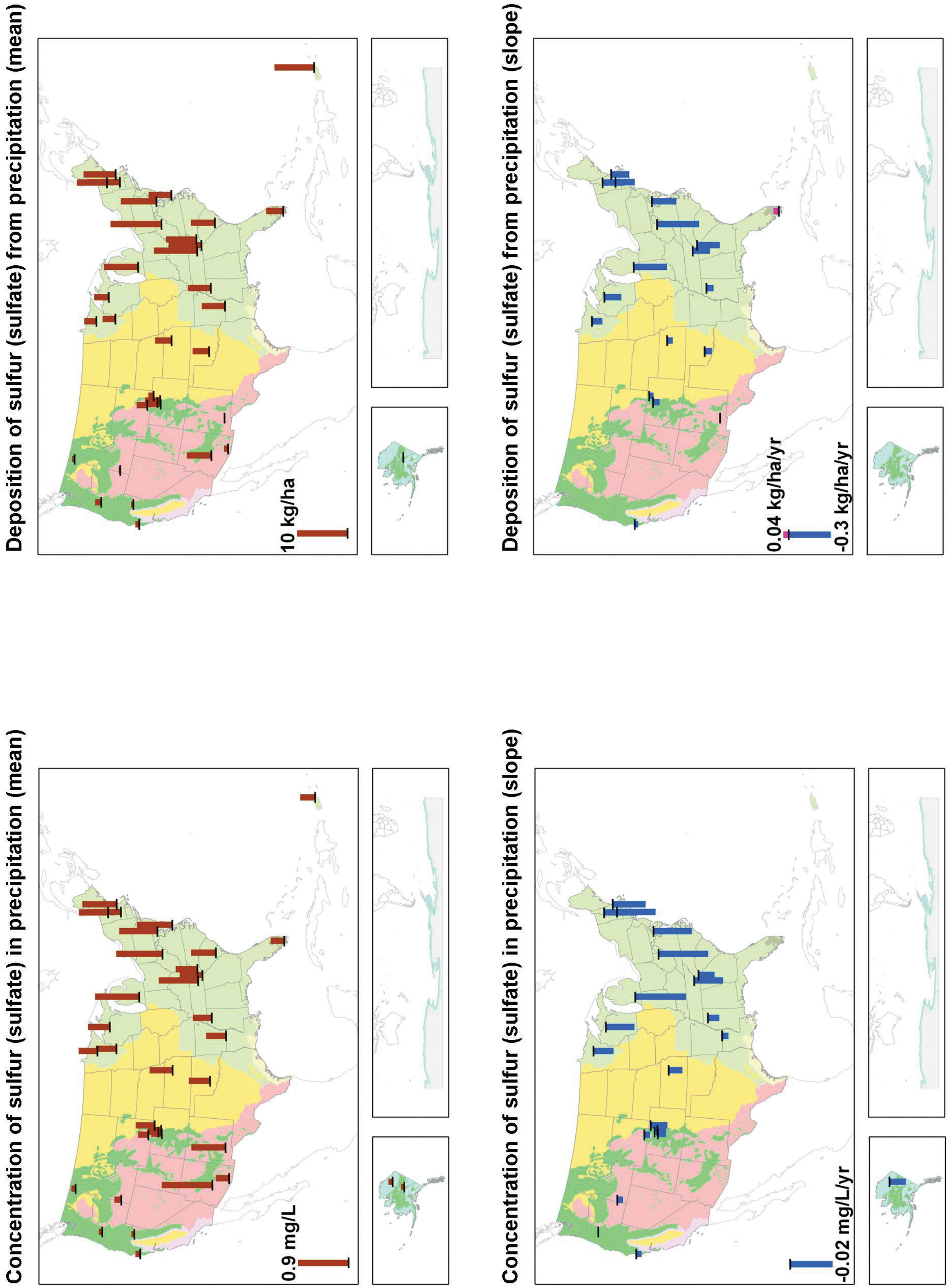


Figure 12-22. Continental patterns in sulfur (sulfate) from precipitation: concentration (volume-weighted concentration, mg/L) and wet deposition (kg/ha). Top panels: long-term averages; positive values are red and negative values are green. Bottom panels: slopes of significant regression lines ($p < 0.05$); 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.

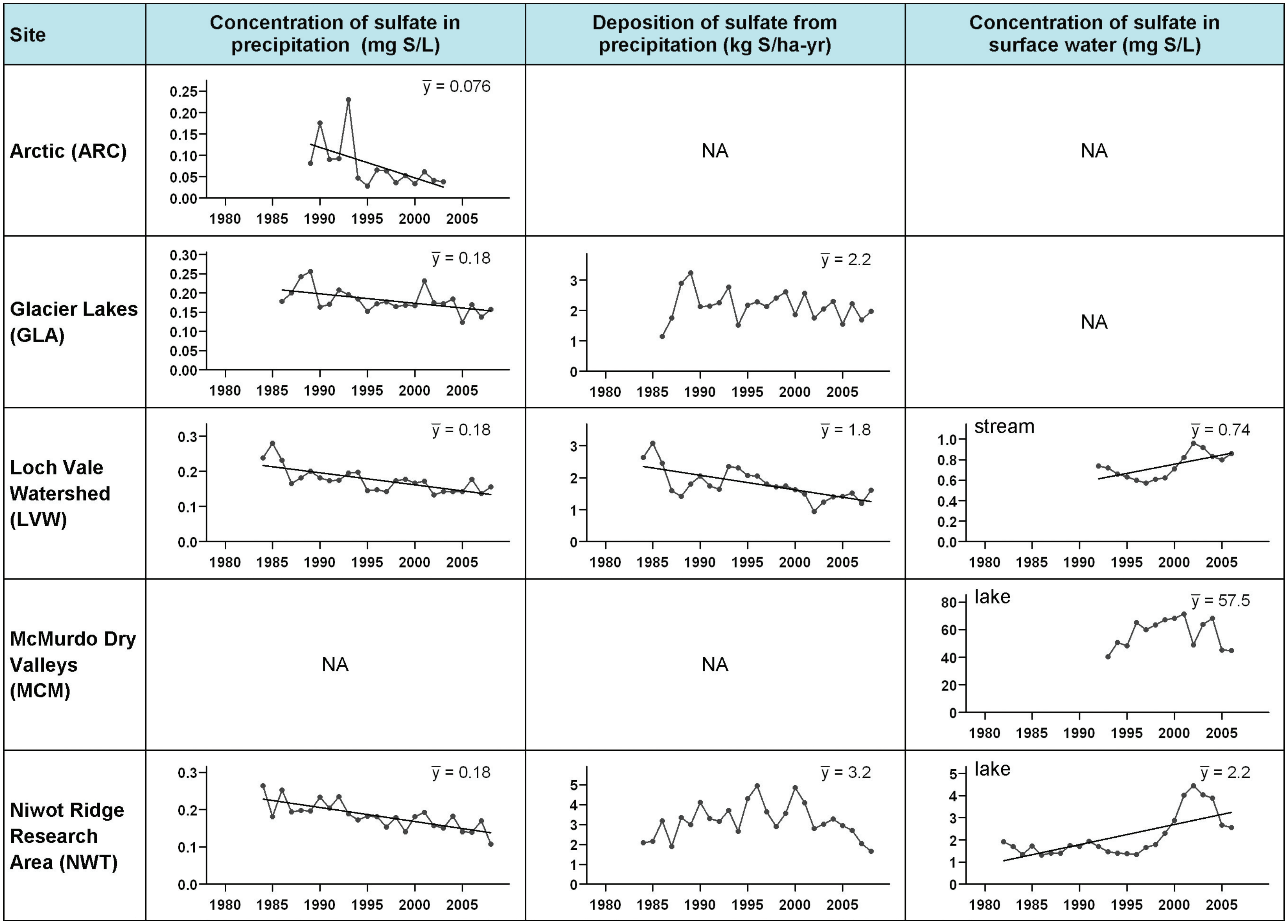


Figure 12-23. Trends for each alpine and arctic site: sulfate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, 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.

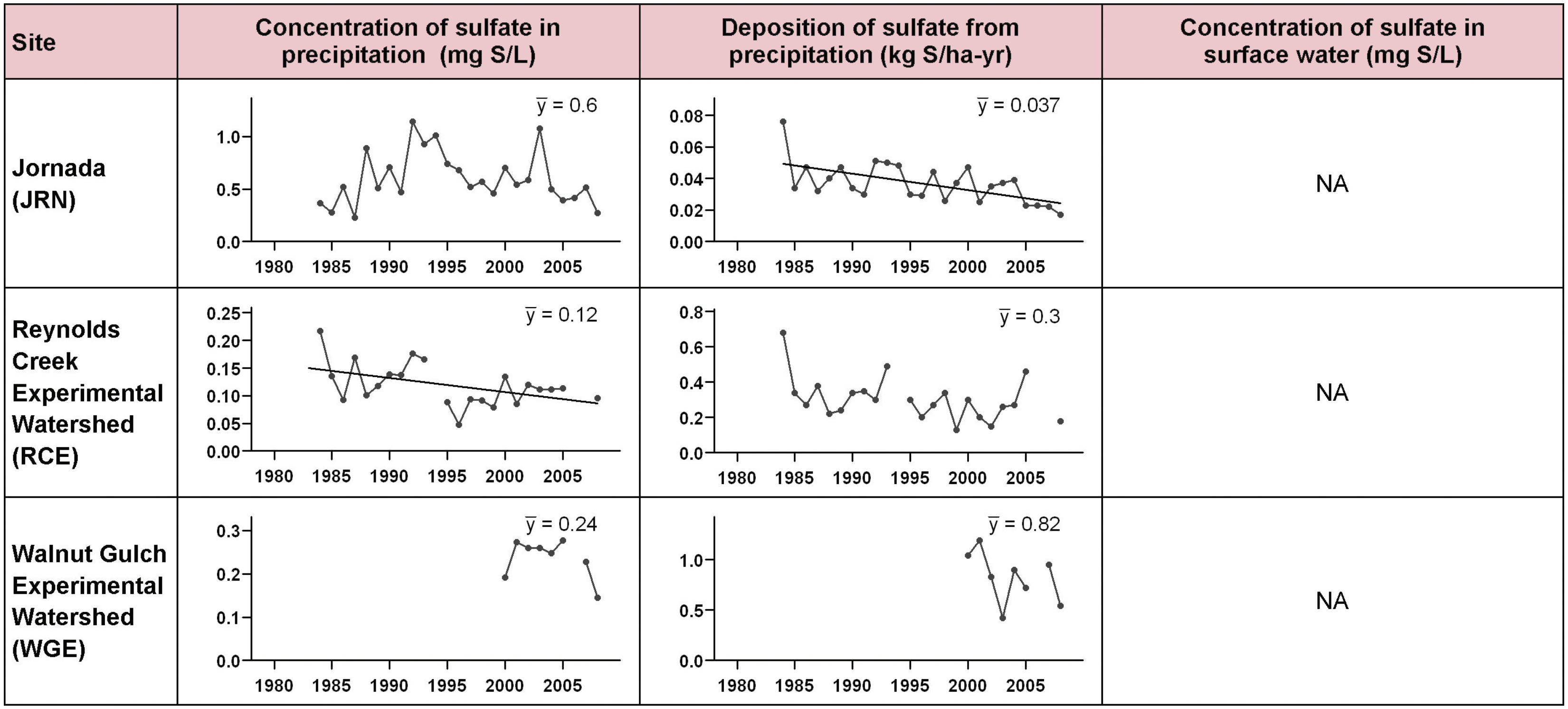


Figure 12-24. Trends for each aridland site: sulfate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, 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.

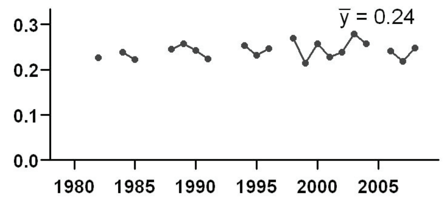
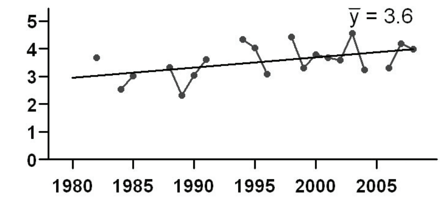
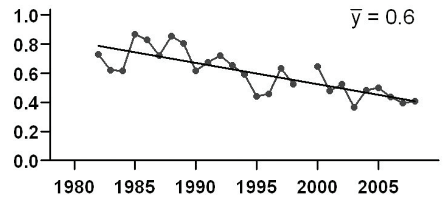
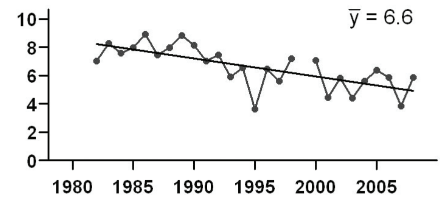
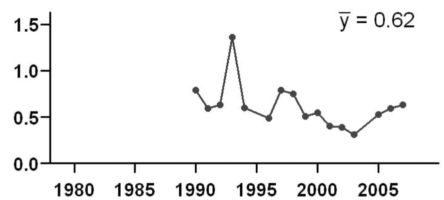
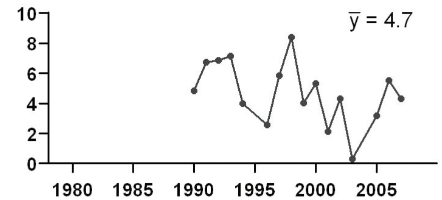
Site	Concentration of sulfate in precipitation (mg S/L)	Deposition of sulfate from precipitation (kg S/ha-yr)	Concentration of sulfate in surface water (mg S/L)
Florida Coastal Everglades (FCE)			NA
Plum Island Ecosystems (PIE)			NA
Virginia Coast Reserve (VCR)			NA

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.

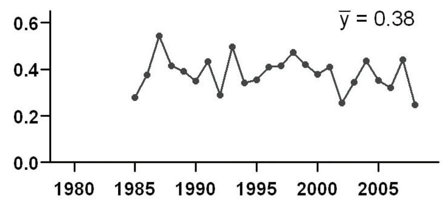
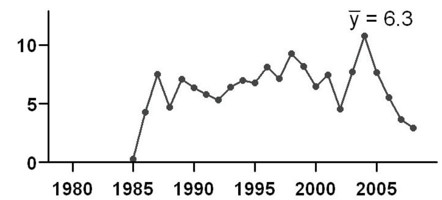
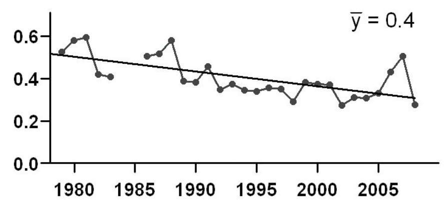
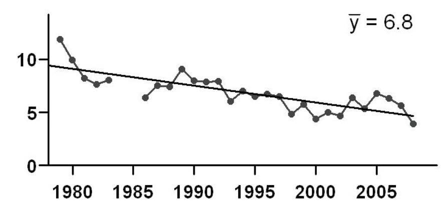
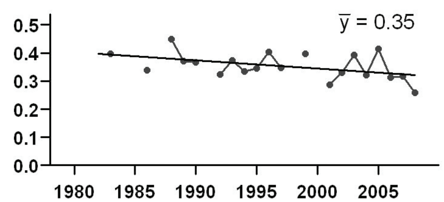
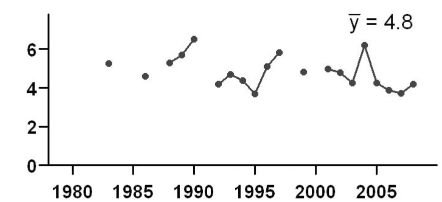
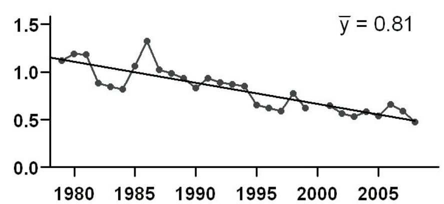
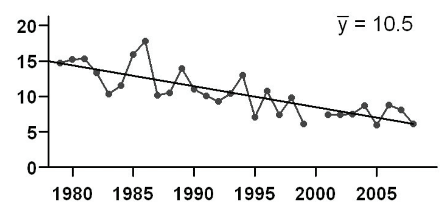
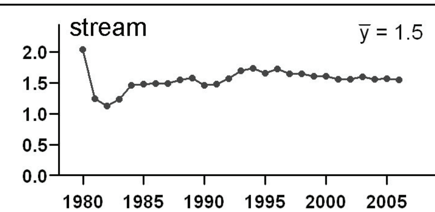
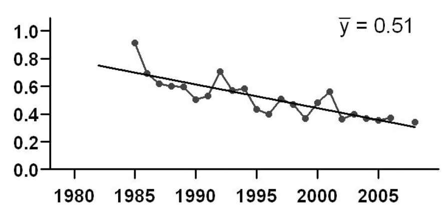
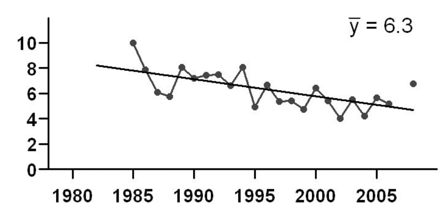
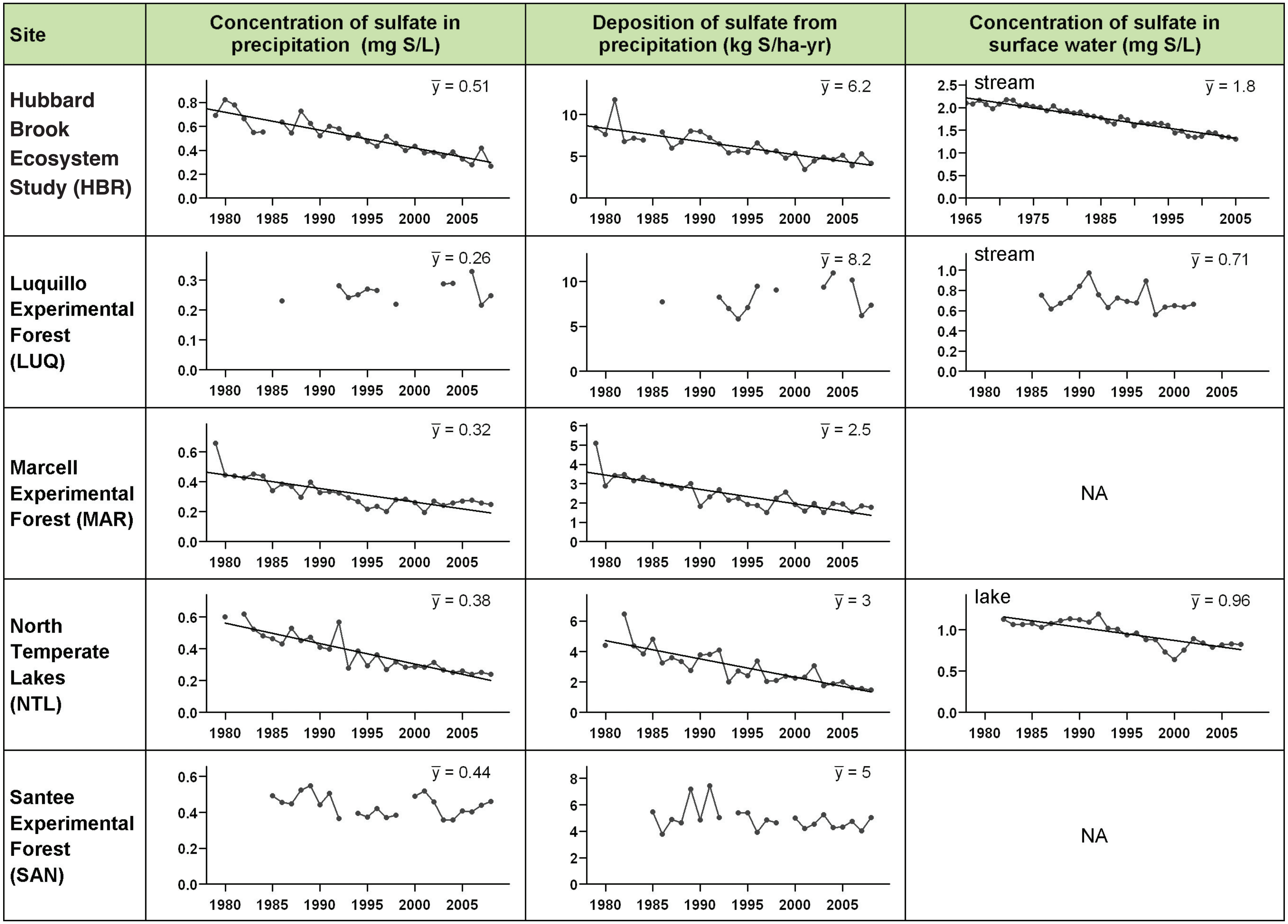
Site	Concentration of sulfate in precipitation (mg S/L)	Deposition of sulfate from precipitation (kg S/ha-yr)	Concentration of sulfate in surface water (mg S/L)
Bent Creek Experimental Forest (BEN)			NA
Coweeta (CWT)			NA
Crossett Experimental Forest (CRO)			NA
Fernow Experimental Forest (FER)			
Harvard Forest (HFR)			NA

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



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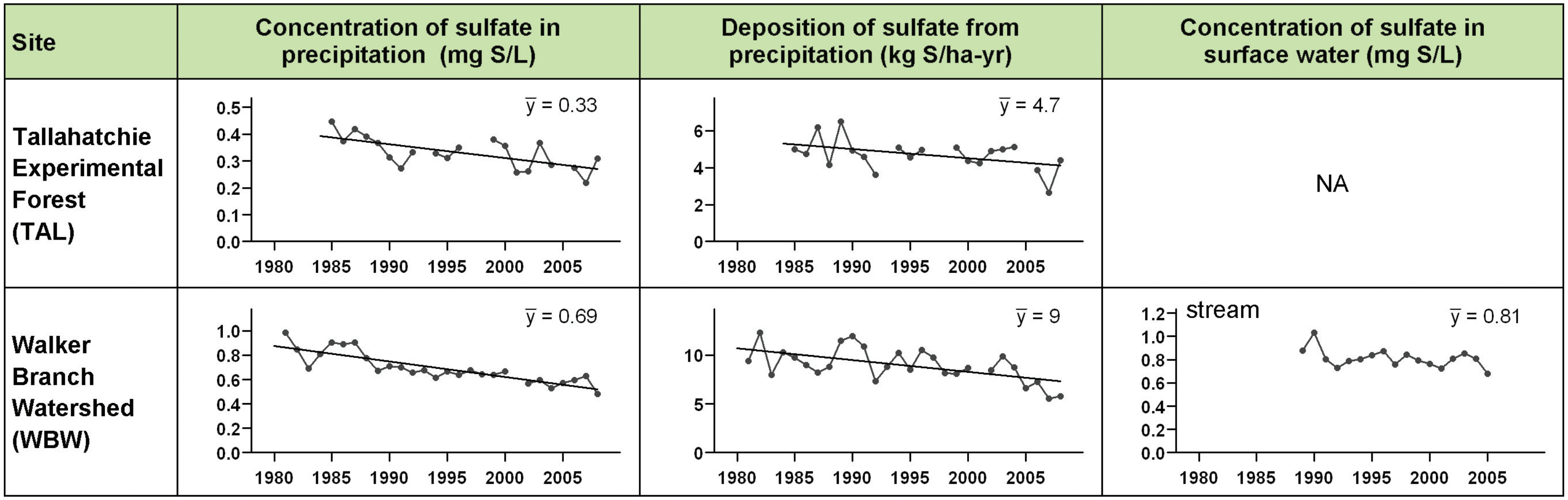


Figure 12-26. Trends for each eastern forest site: sulfate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, 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.

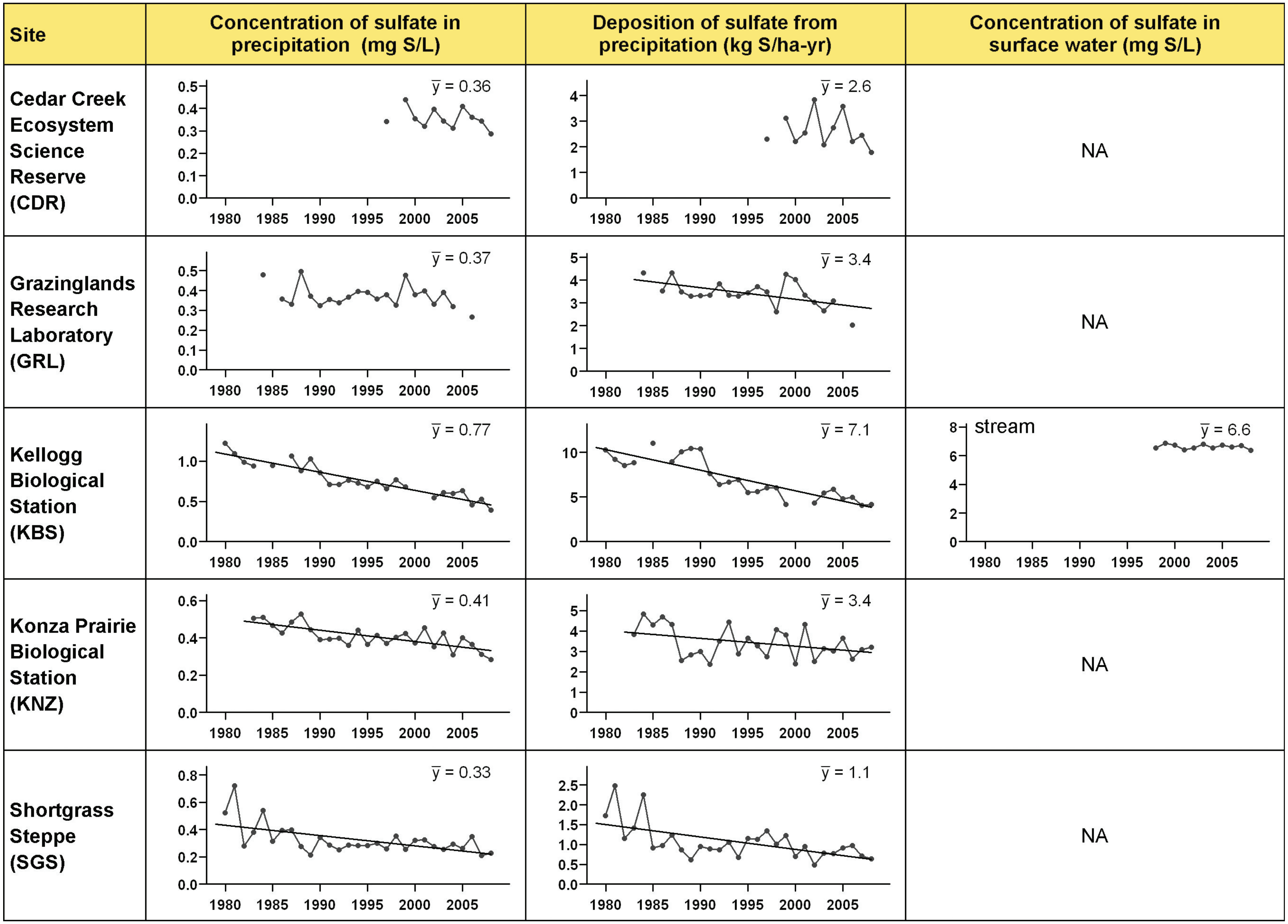


Figure 12-27. Trends for each temperate grassland and savanna site: sulfate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and 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.

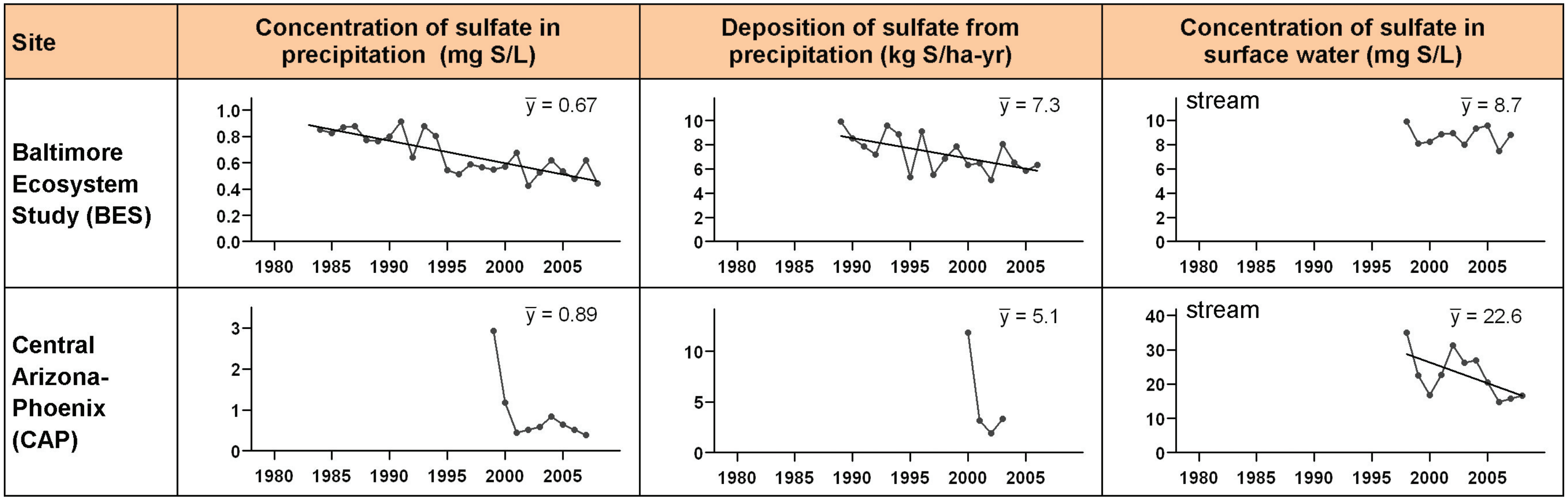


Figure 12-28. Trends for each urban site: sulfate concentration in precipitation, wet deposition, and surface water. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The slopes for concentration in precipitation, wet deposition, and surface water, respectively, 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.

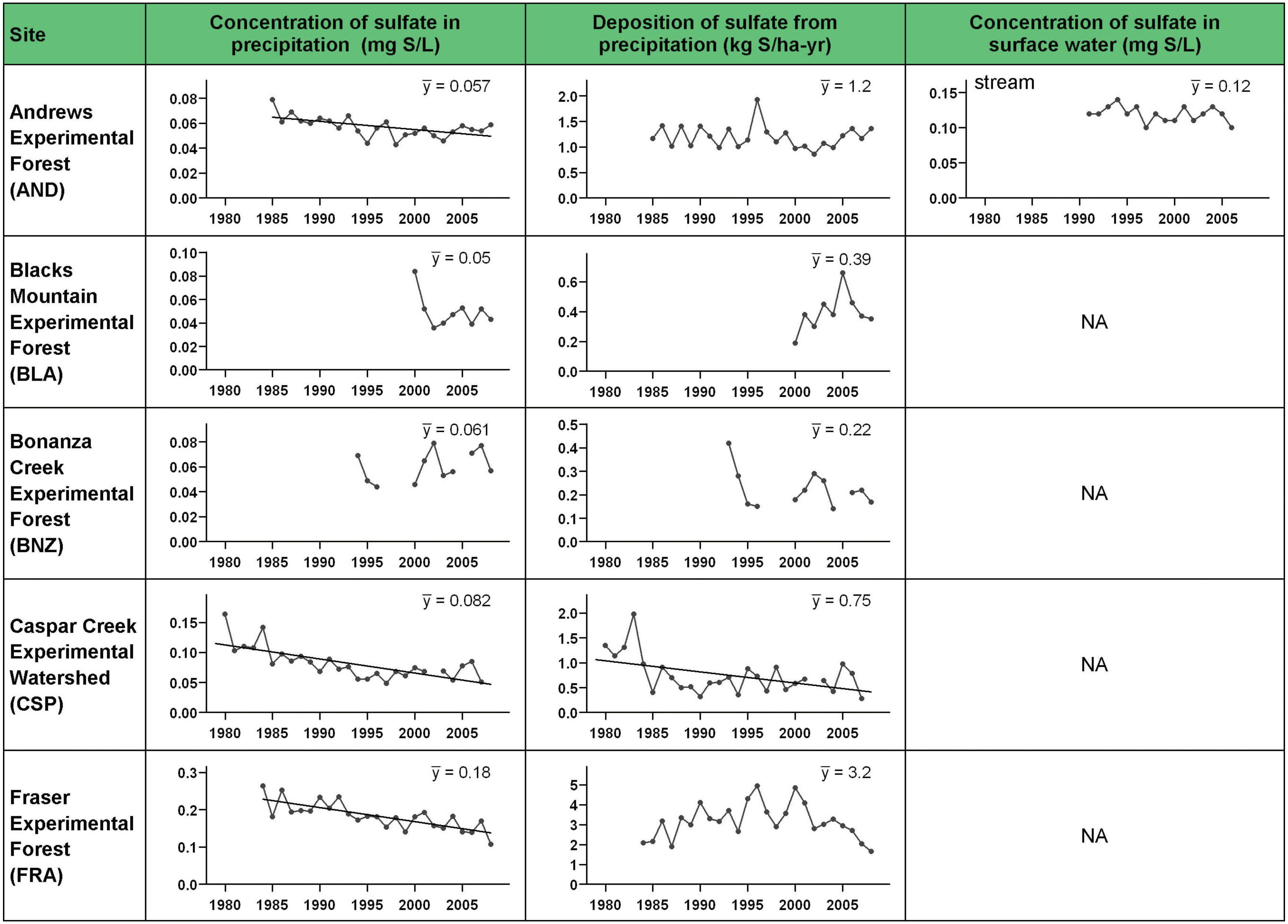


Figure 12-29 (western forest sites) continued next page.

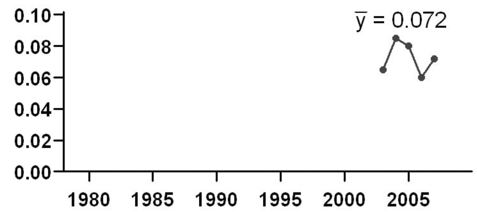
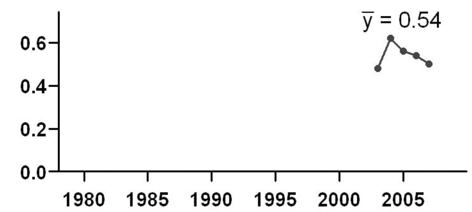
Site	Concentration of sulfate in precipitation (mg S/L)	Deposition of sulfate from precipitation (kg S/ha-yr)	Concentration of sulfate in surface water (mg S/L)
Priest River Experimental Forest (PRI)			NA

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.

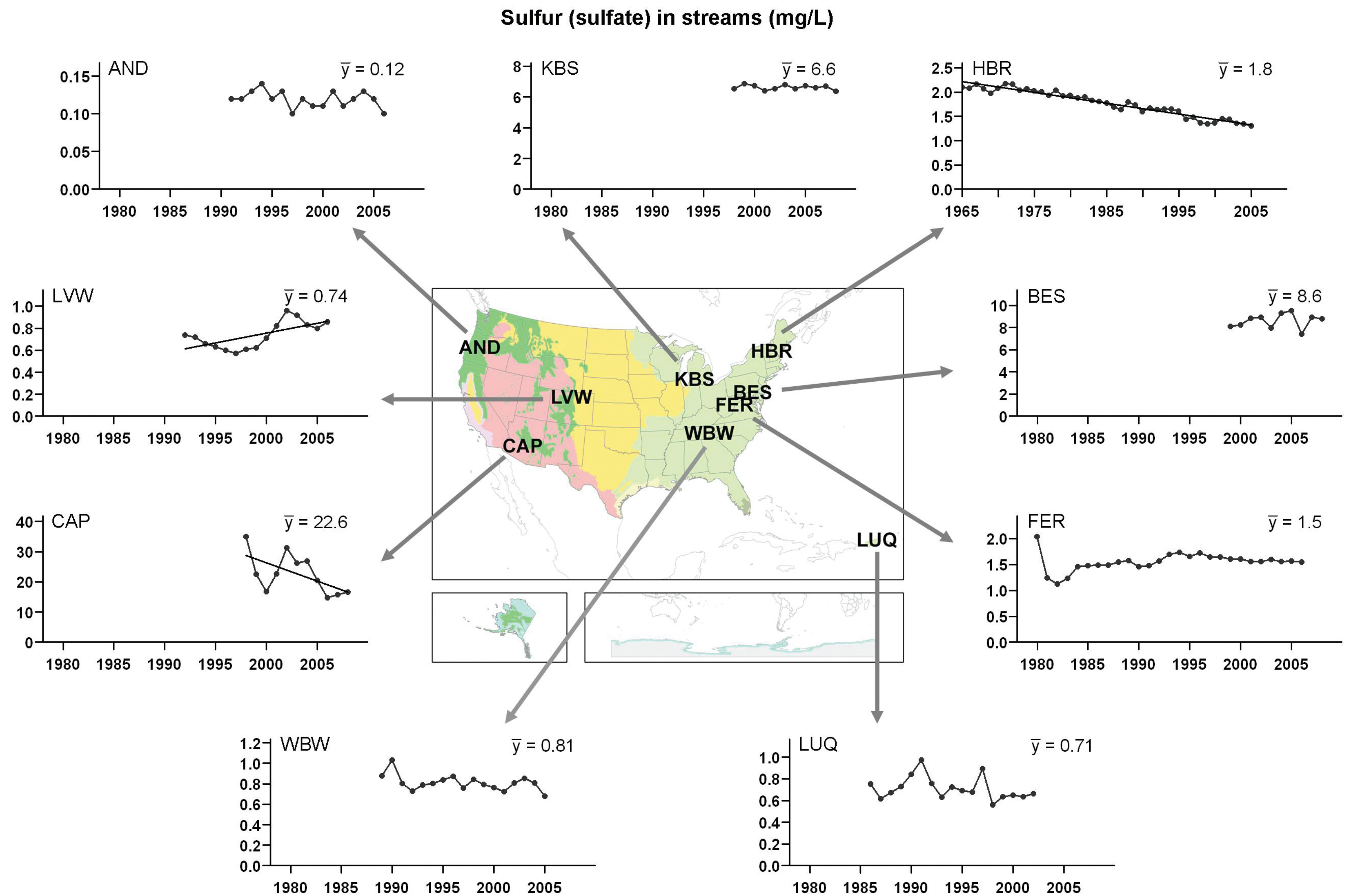


Figure 12-30. Concentration of sulfur (sulfate, mg/L) in streams through time at nine sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Central Arizona-Phoenix (CAP) (-1.22), Hubbard Brook Ecosystem Study (HBR) (-0.02), and 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.

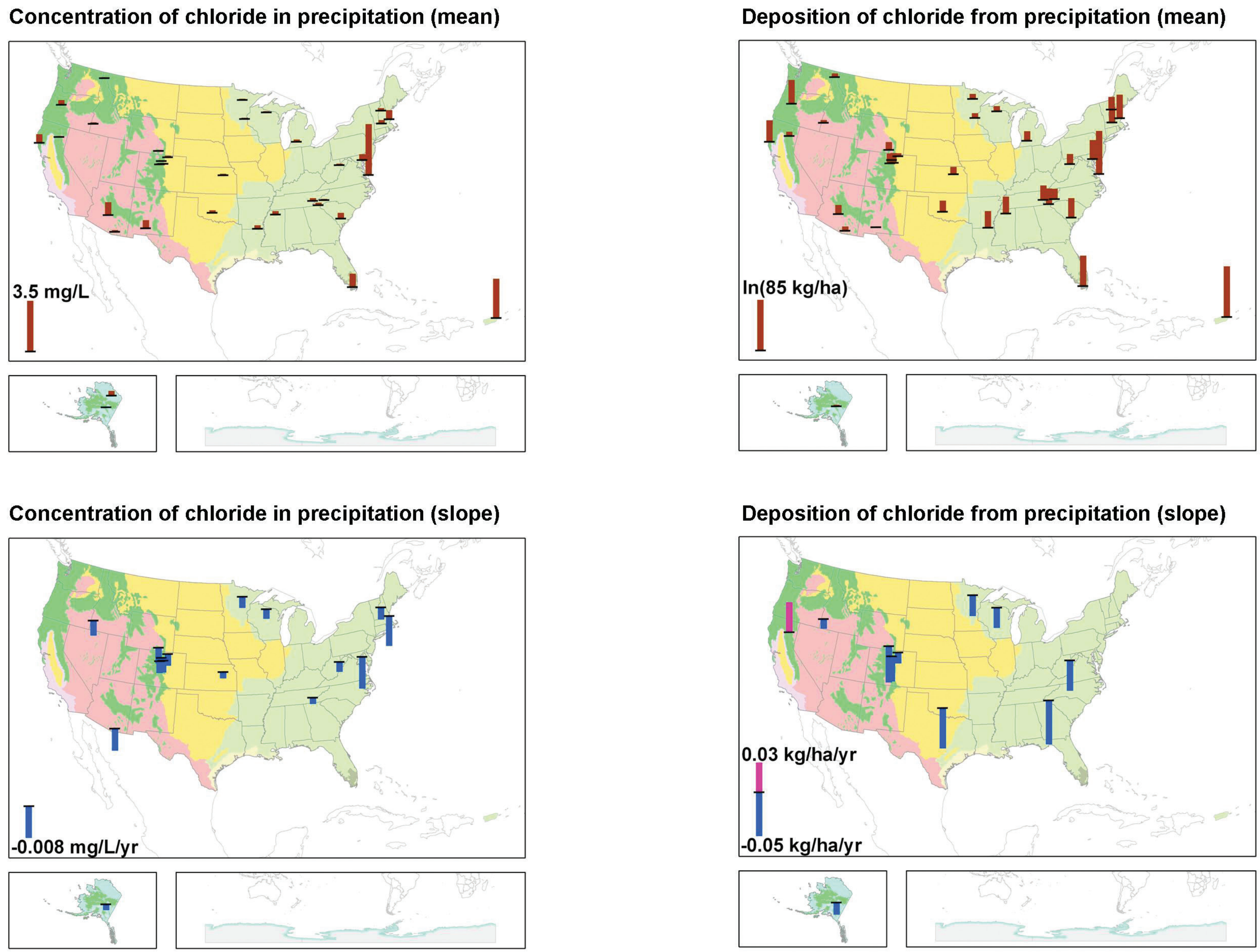


Figure 12-31. Continental patterns in chloride from precipitation: concentration (volume-weighted concentration, mg/L) and wet deposition (kg/ha). Top panels: long-term averages; positive values are red and negative values are green. Bottom panels: slopes of significant regression lines ($p < 0.05$); 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.

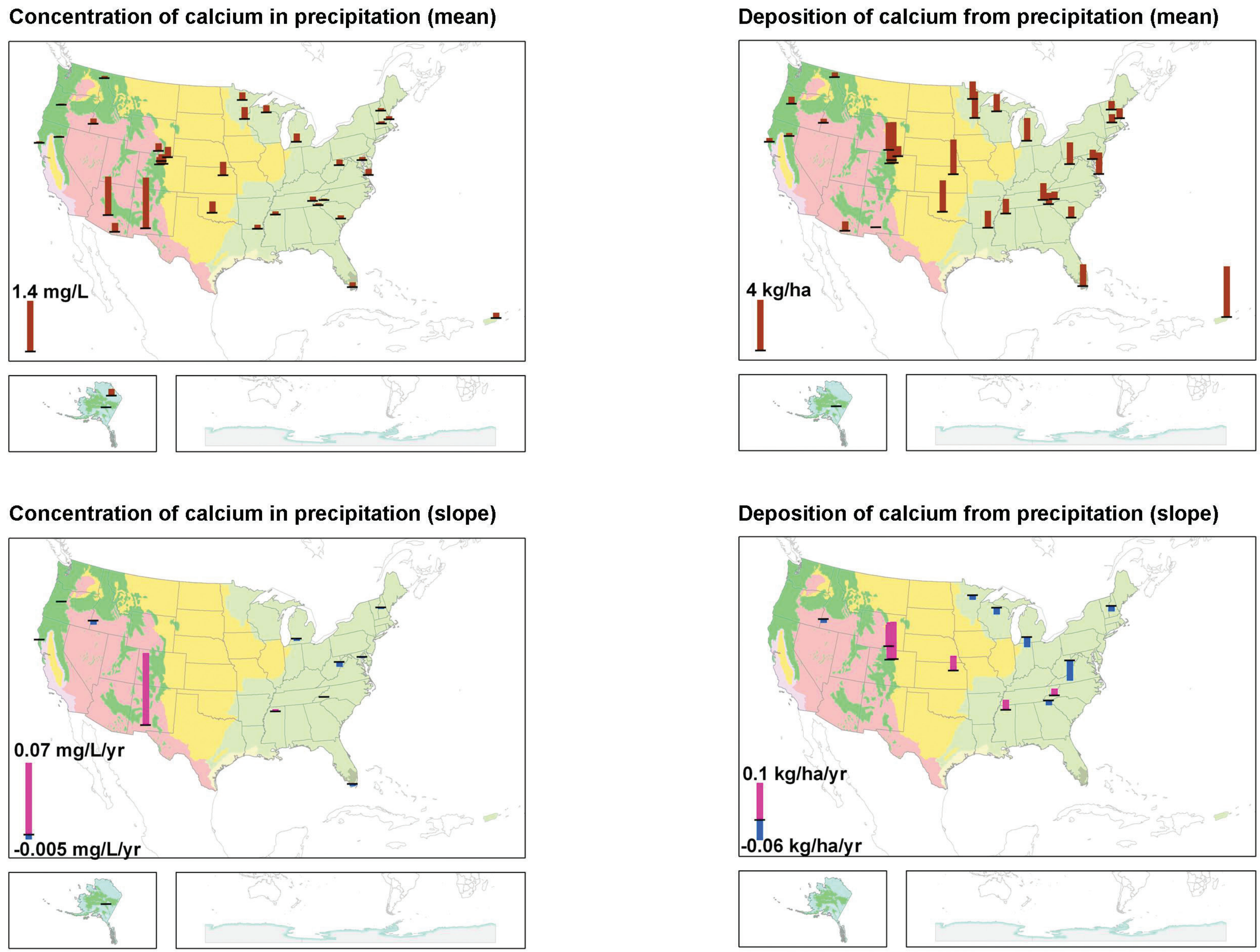


Figure 12-32. Continental patterns in calcium from precipitation: concentration (volume-weighted concentration, mg/L) and wet deposition (kg/ha). Top panels: long-term averages; positive values are red and negative values are green. Bottom panels: slopes of significant regression lines ($p < 0.05$); 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.

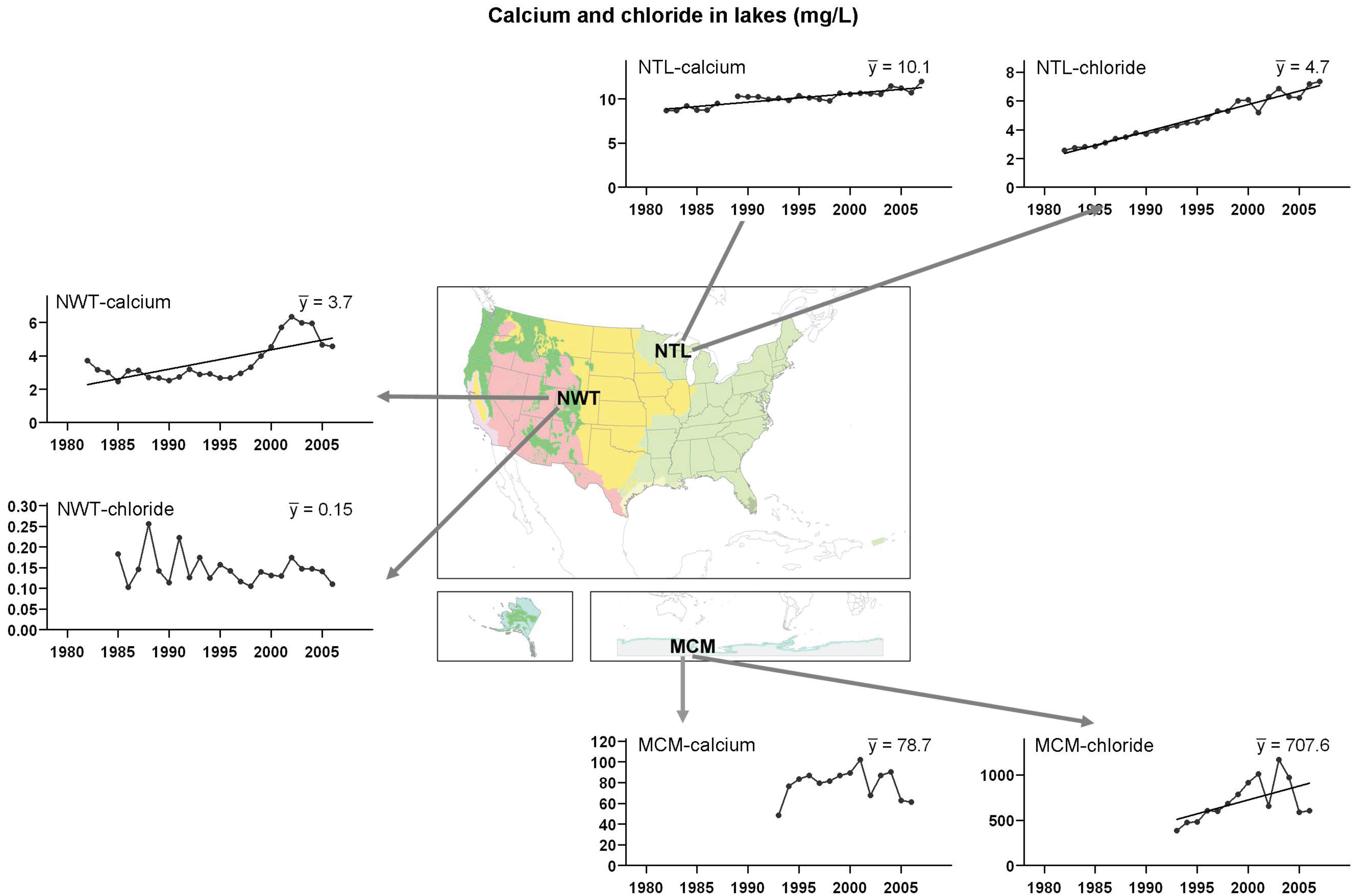


Figure 12-33. Concentrations of calcium and chloride (mg/L) in lakes through time at three sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are McMurdo Dry Valleys (MCM) (30.38 chloride), North Temperate Lakes (NTL) (0.10 calcium, 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.

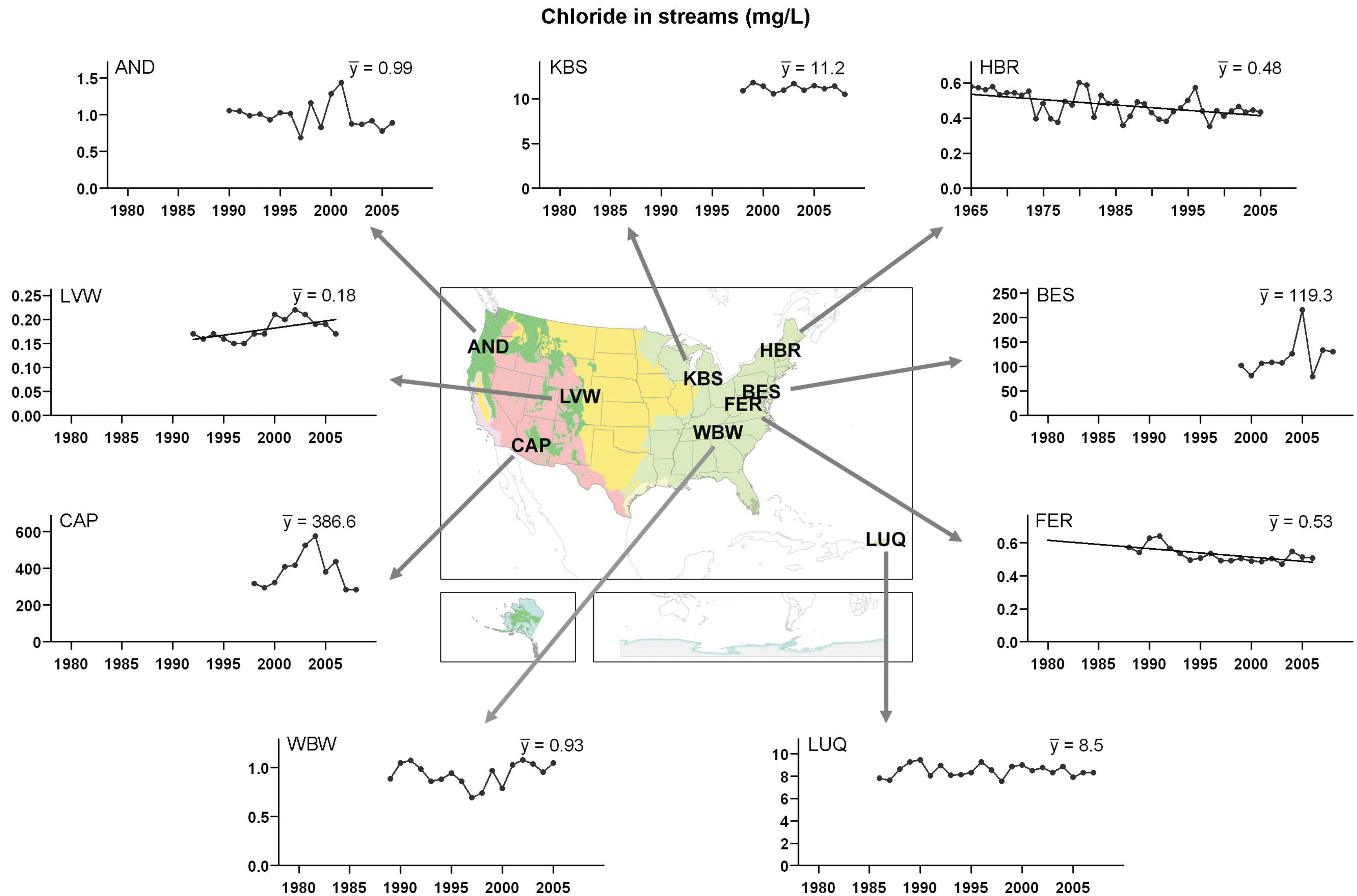


Figure 12-34. Concentration of chloride (mg/L) in streams through time at nine sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Fernow Experimental Forest (FER) (-0.005), Hubbard Brook Ecosystem Study (HBR) (-0.003), and Loch 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.

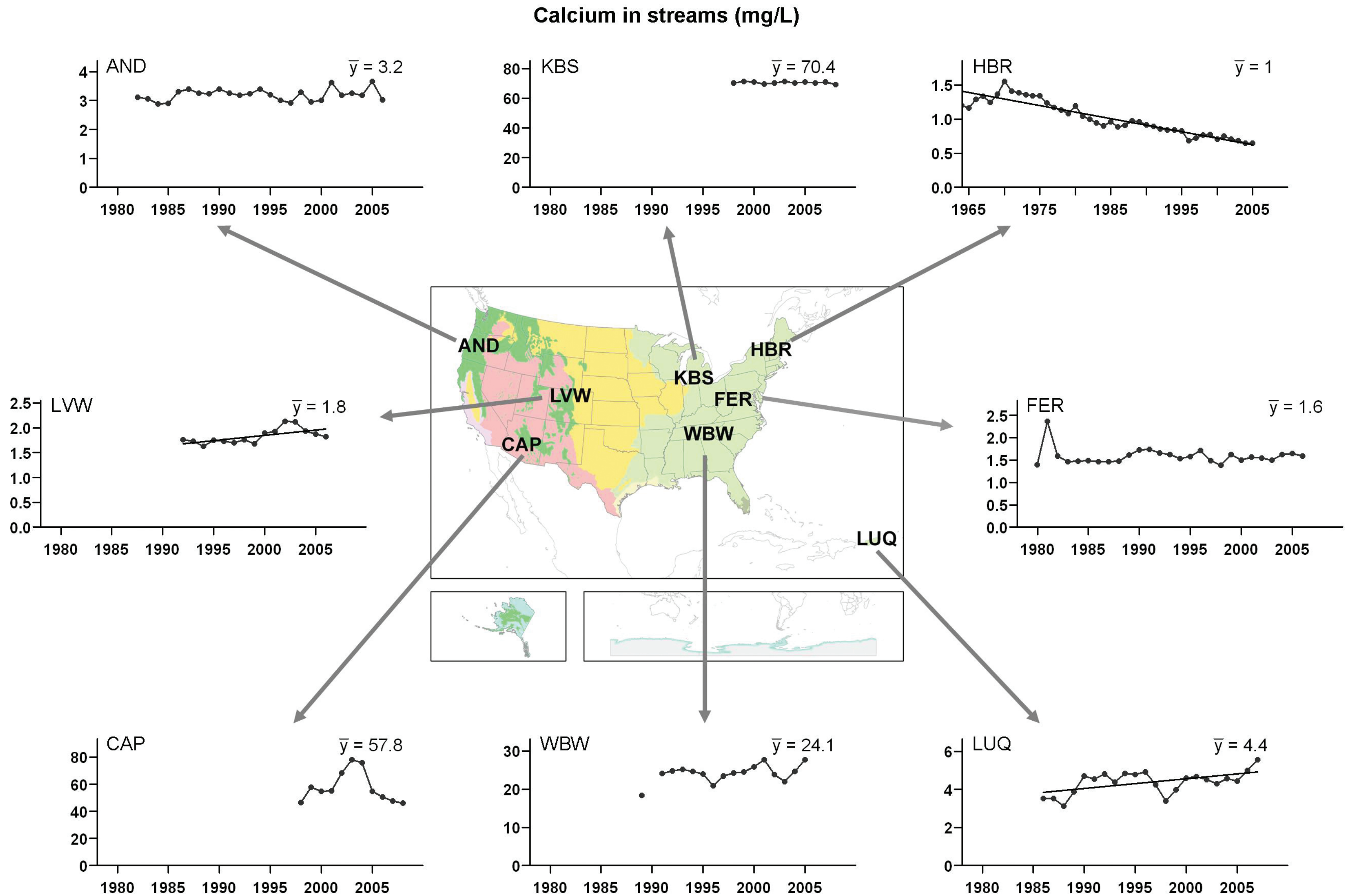


Figure 12-35. Concentration of calcium (mg/L) in streams through time at eight sites. A simple regression line is displayed if the slope is statistically significant ($p < 0.05$). The significant slopes are Hubbard Brook Ecosystem Study (HBR) (-0.02), Luquillo Experimental Forest (LUQ) (0.05), and Loch 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.

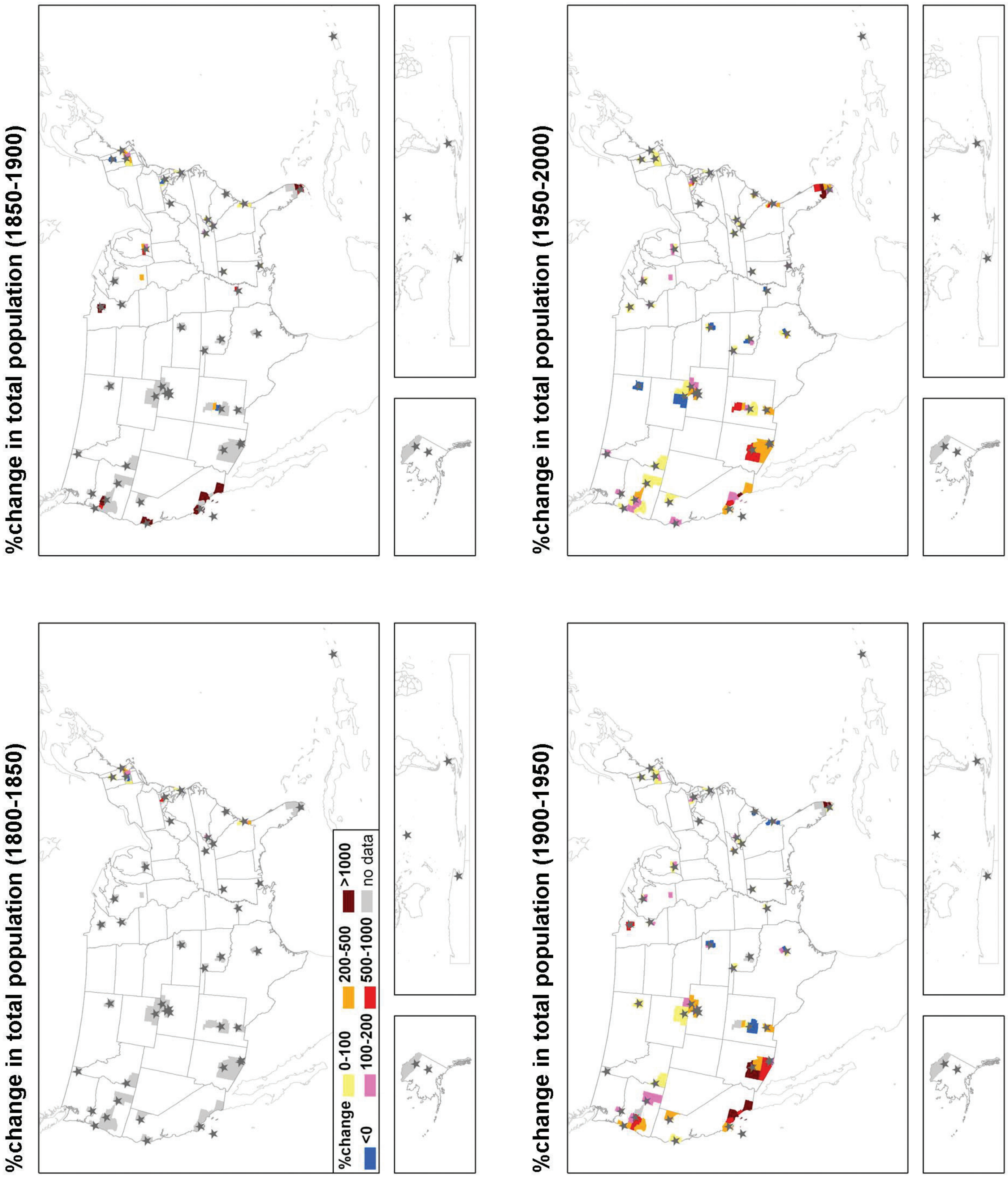


Figure 13-1. Continental pattern of percentage change in total population over time by county calculated as [(year 2 - year 1)/year 1] × 100 for 4 time periods: 1800-1850, 1850-1900, 1900-1950, and 1950-2000. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

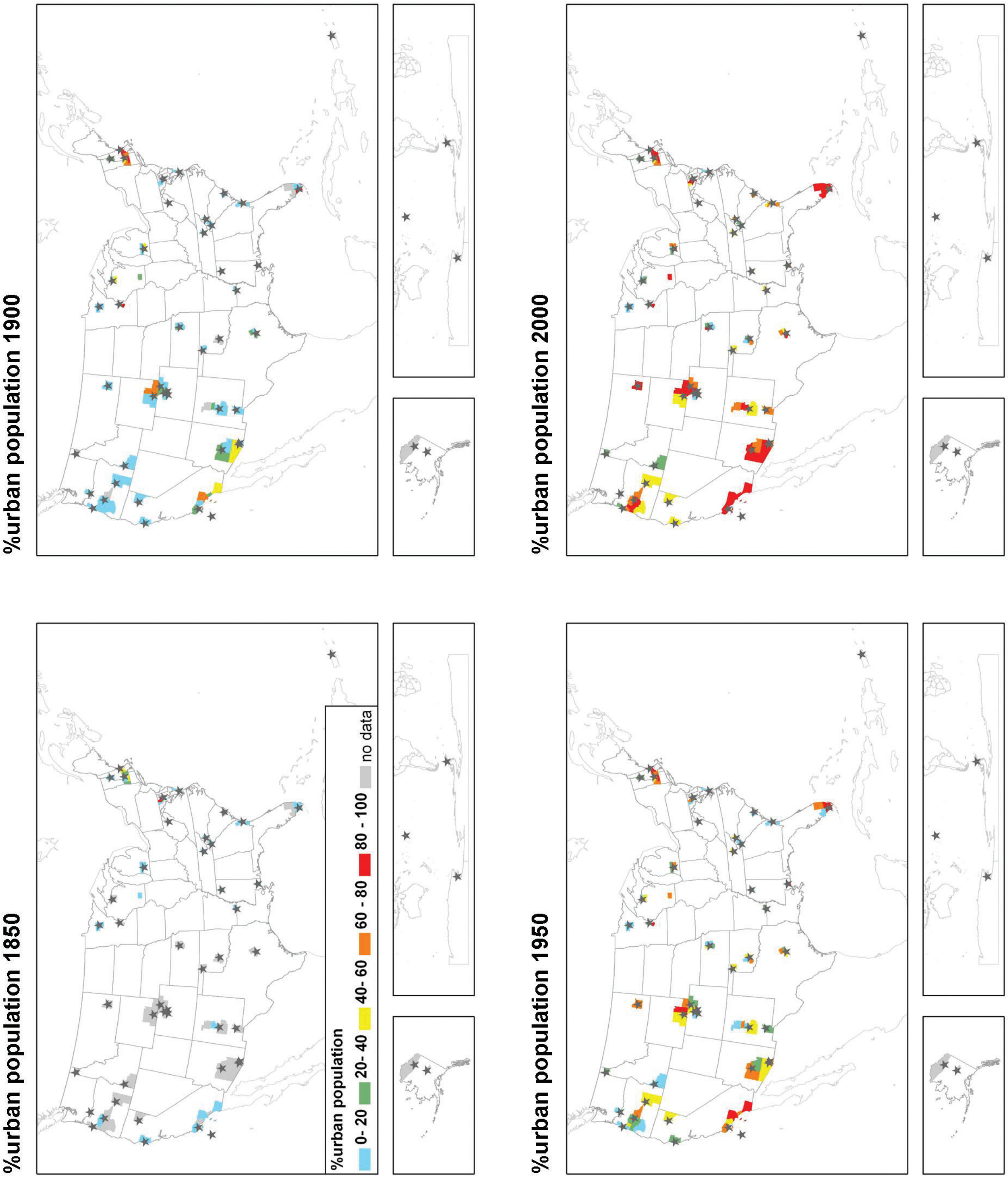


Figure 13-2. Continental pattern of percentage urban population by county over time calculated as (number of people living in urban areas / total number of people) × 100 in 1850, 1900, 1950, and 2000. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

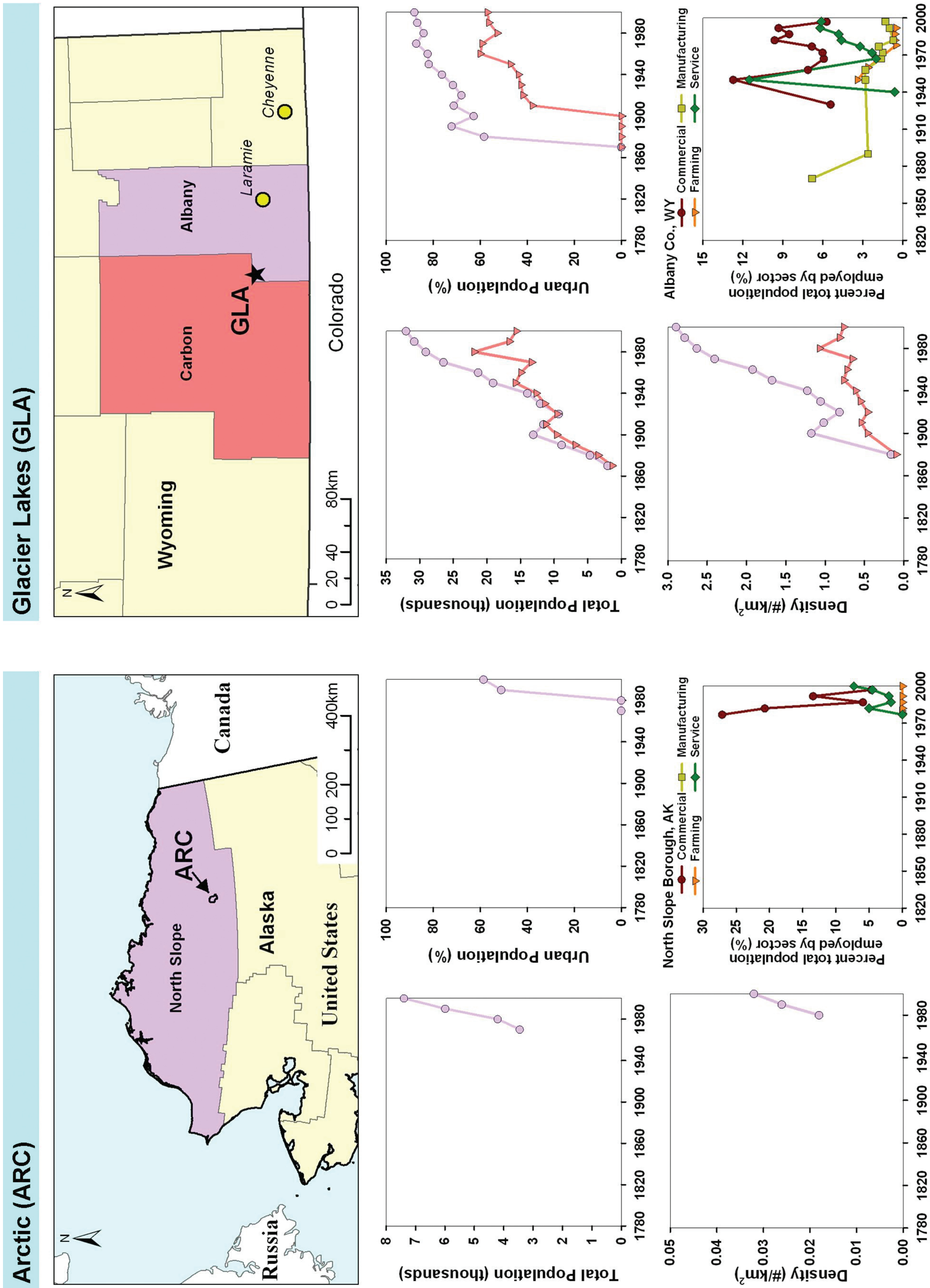


Figure 13-3 (Alpine and Arctic sites) continued next page.

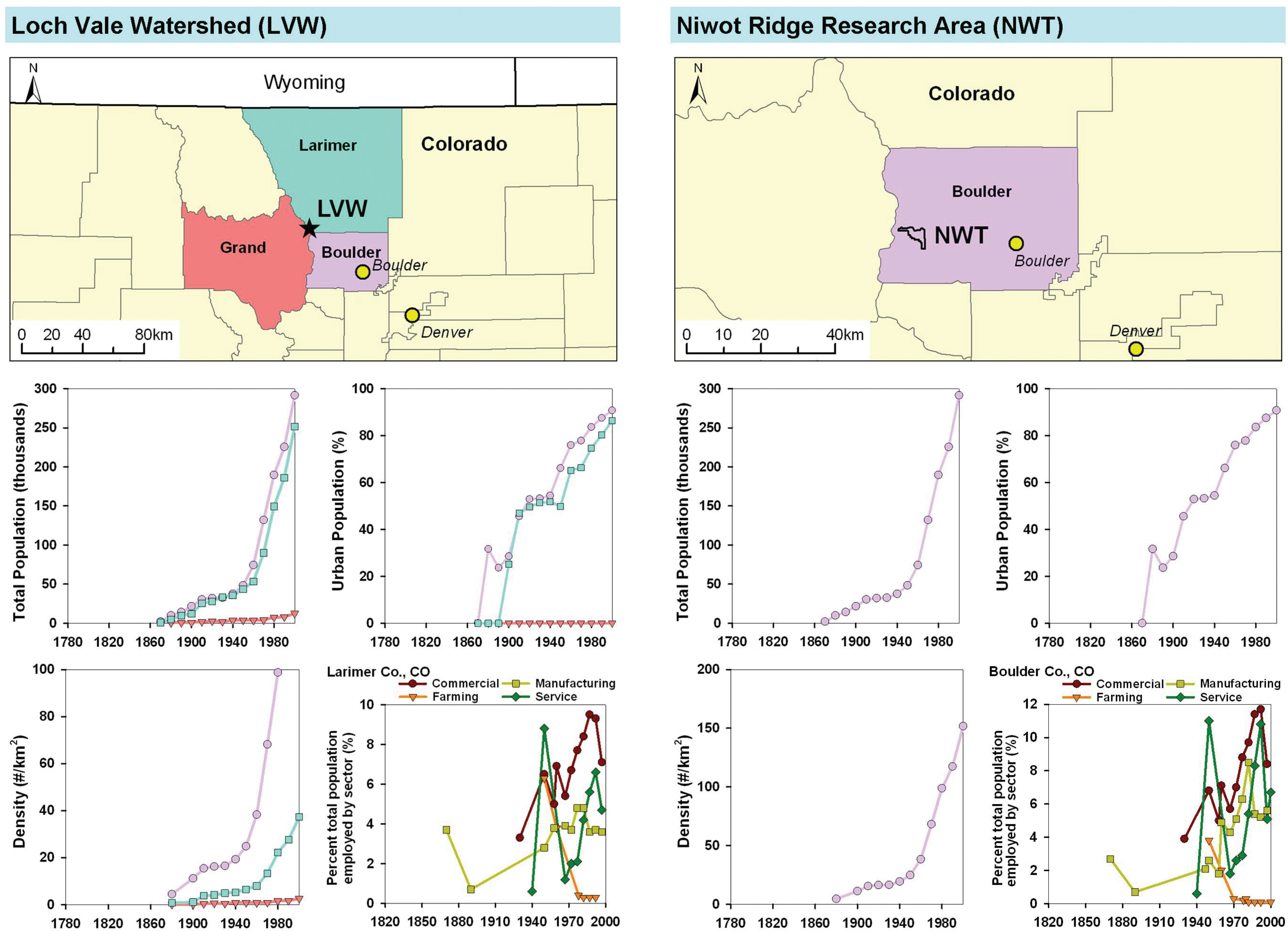


Figure 13-3. Trends for each alpine and arctic site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and percentage of total population employed by four sectors 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.

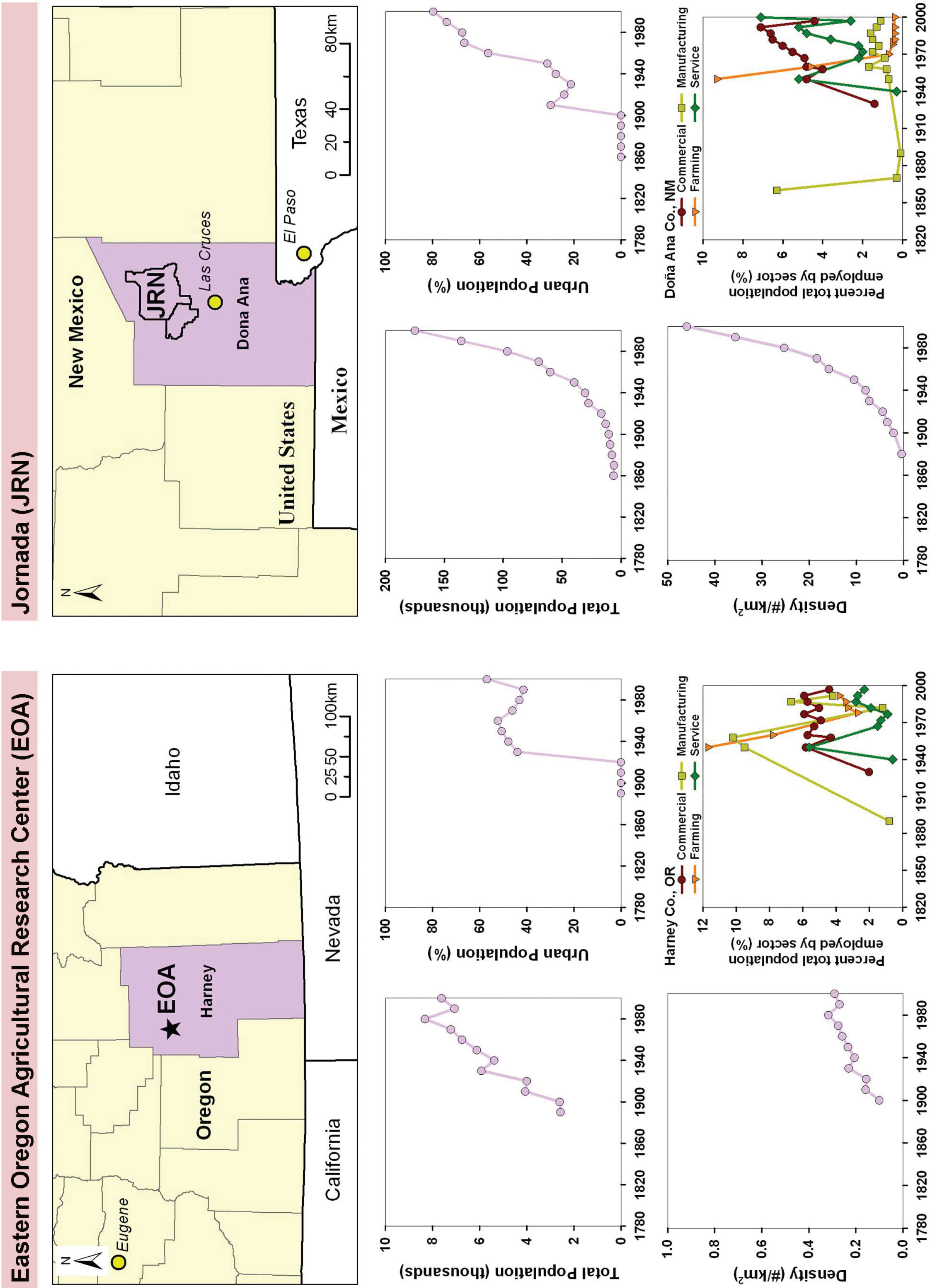


Figure 13-4 (aridland sites) continued next page.

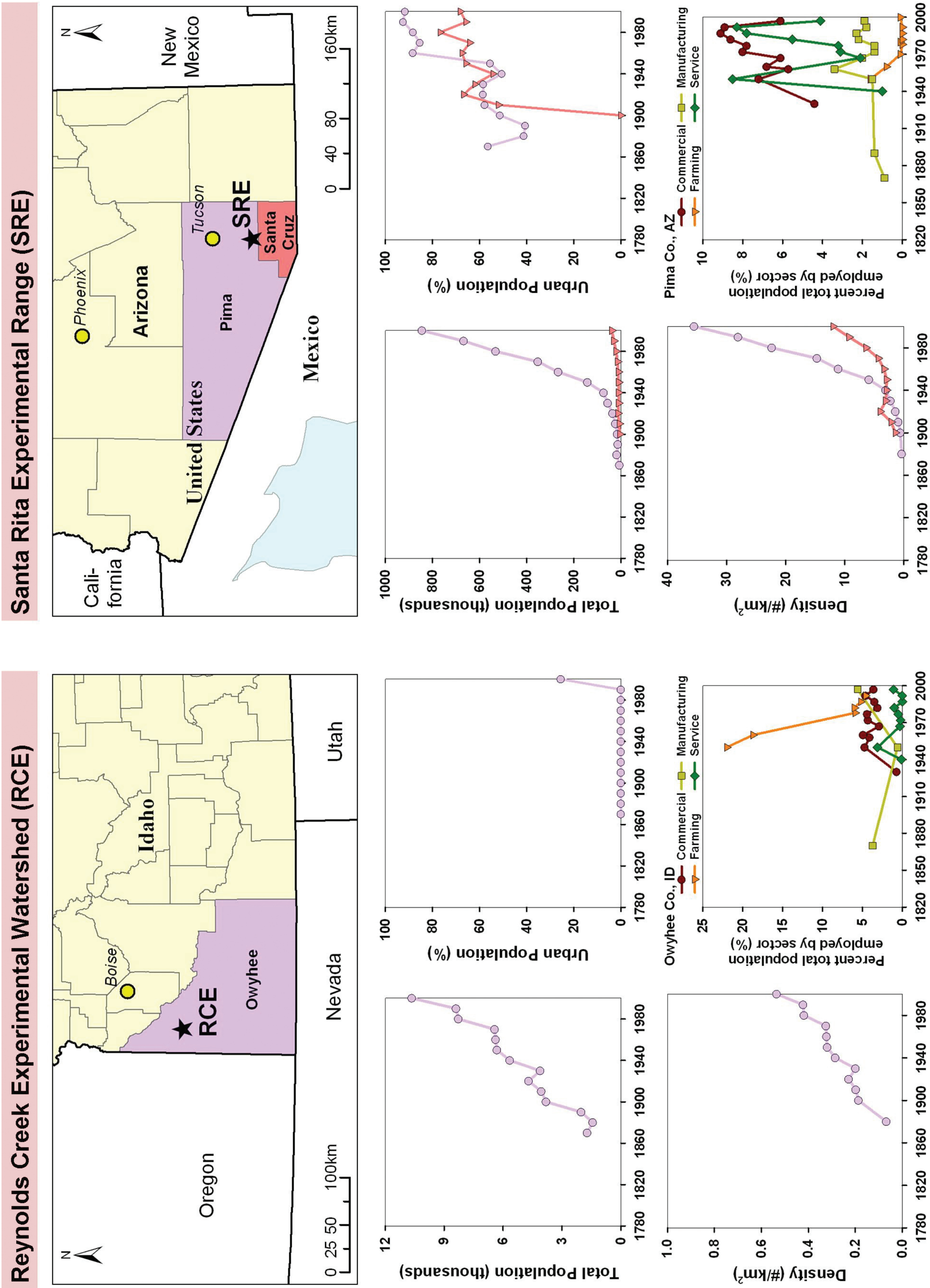


Figure 13-4 (aridland sites) continued next page.

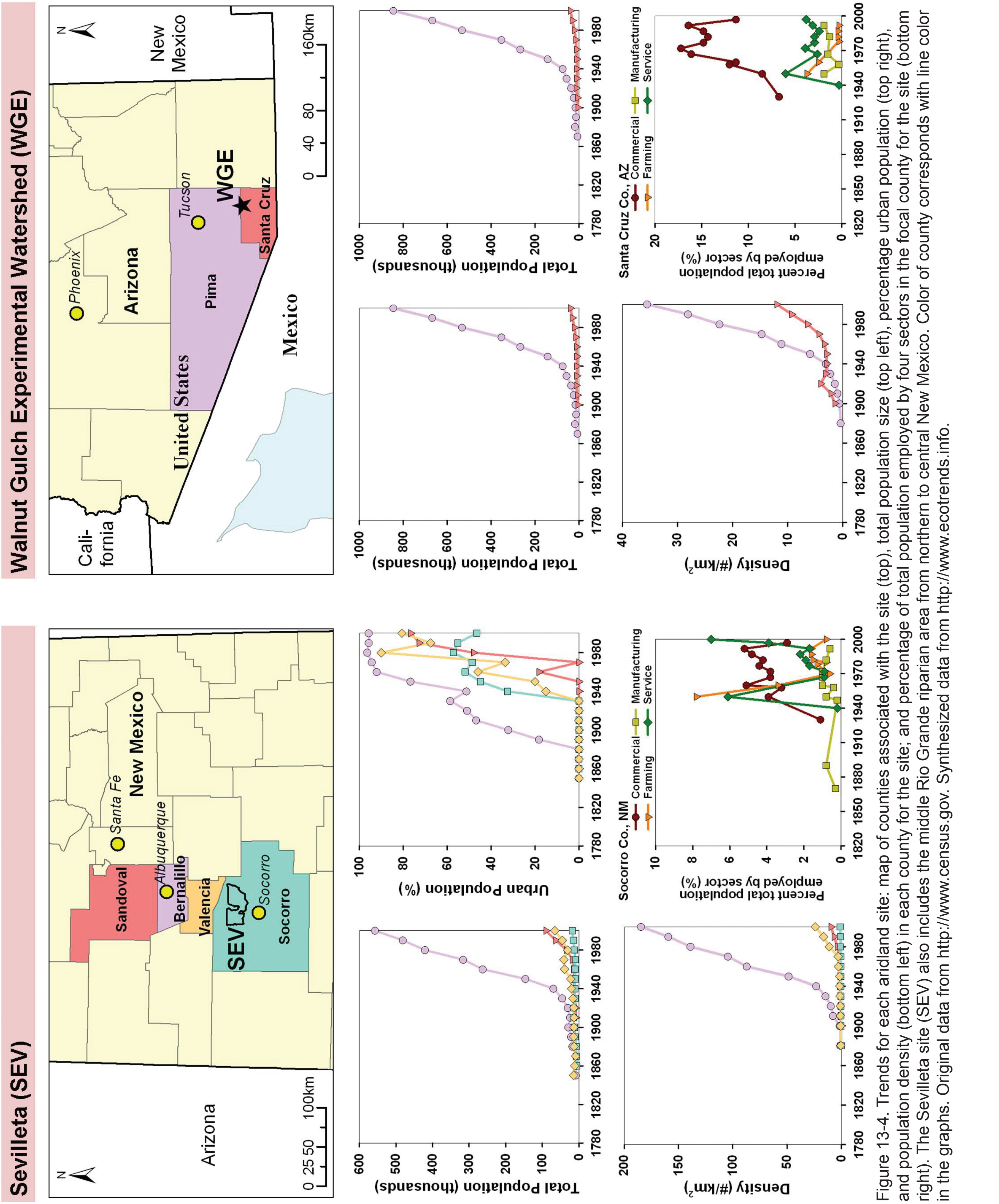


Figure 13-4. Trends for each aridland site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and percentage of total population employed by four sectors in the focal 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.

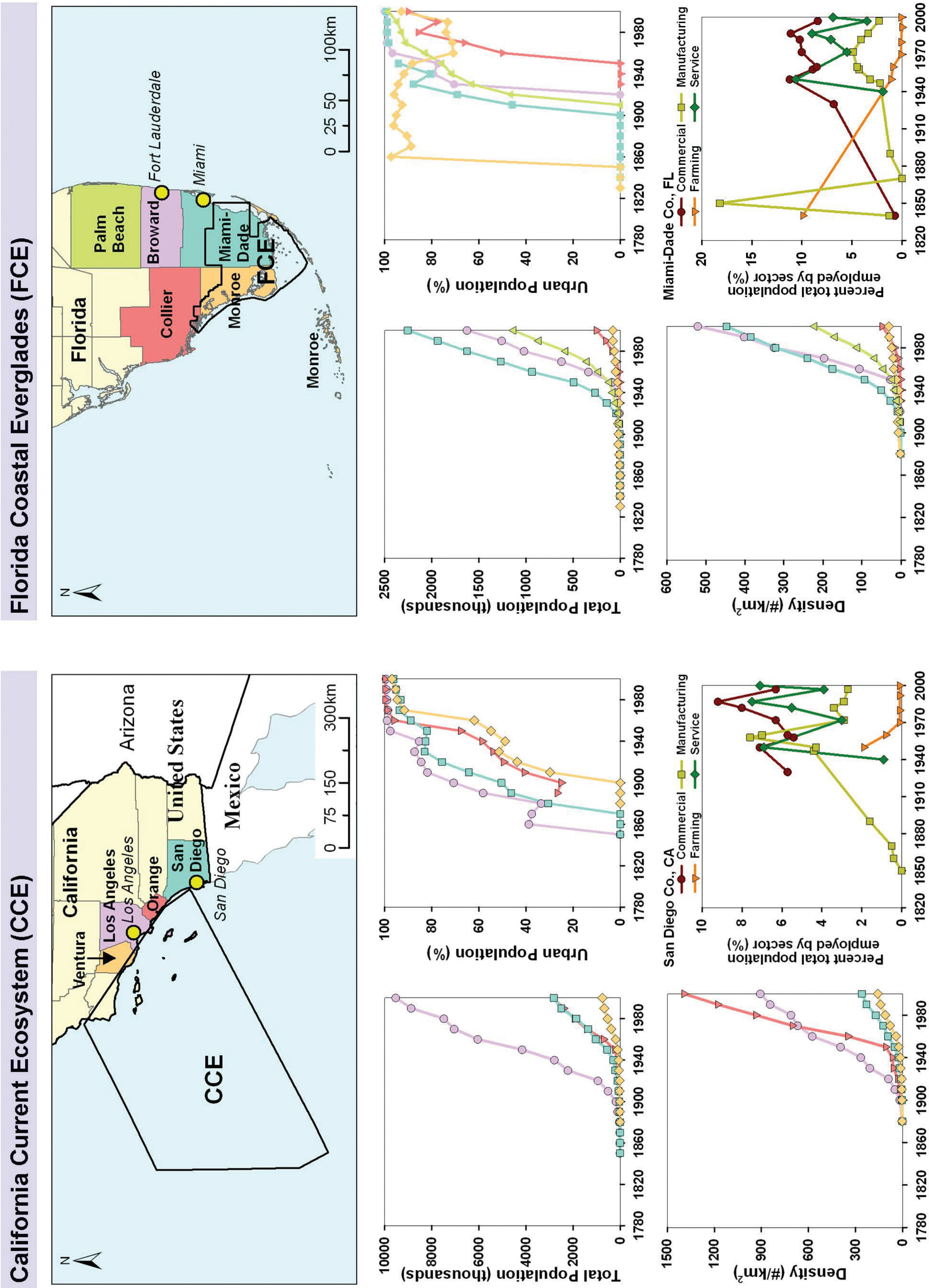
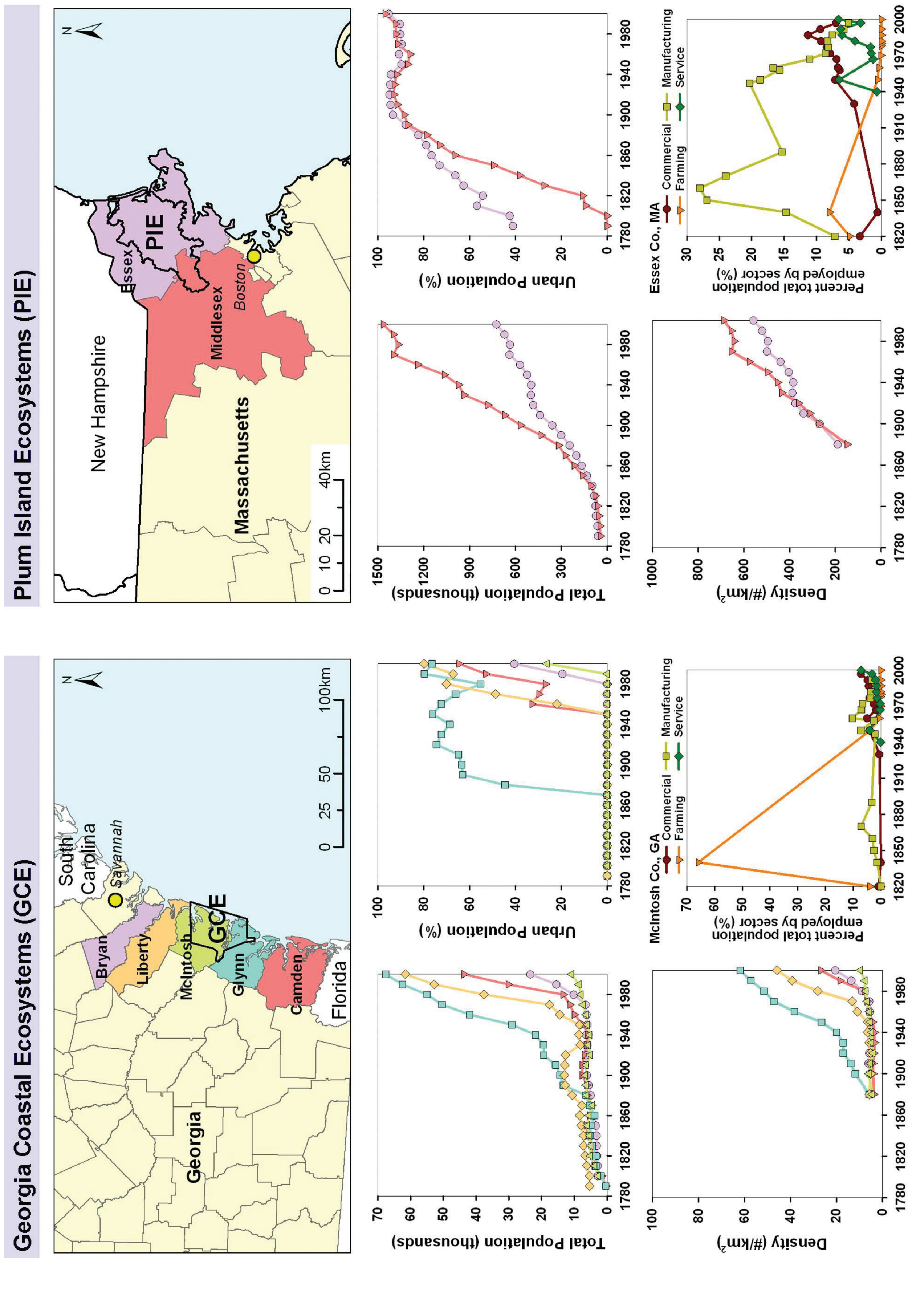


Figure 13-5 (coastal sites) continued next page.



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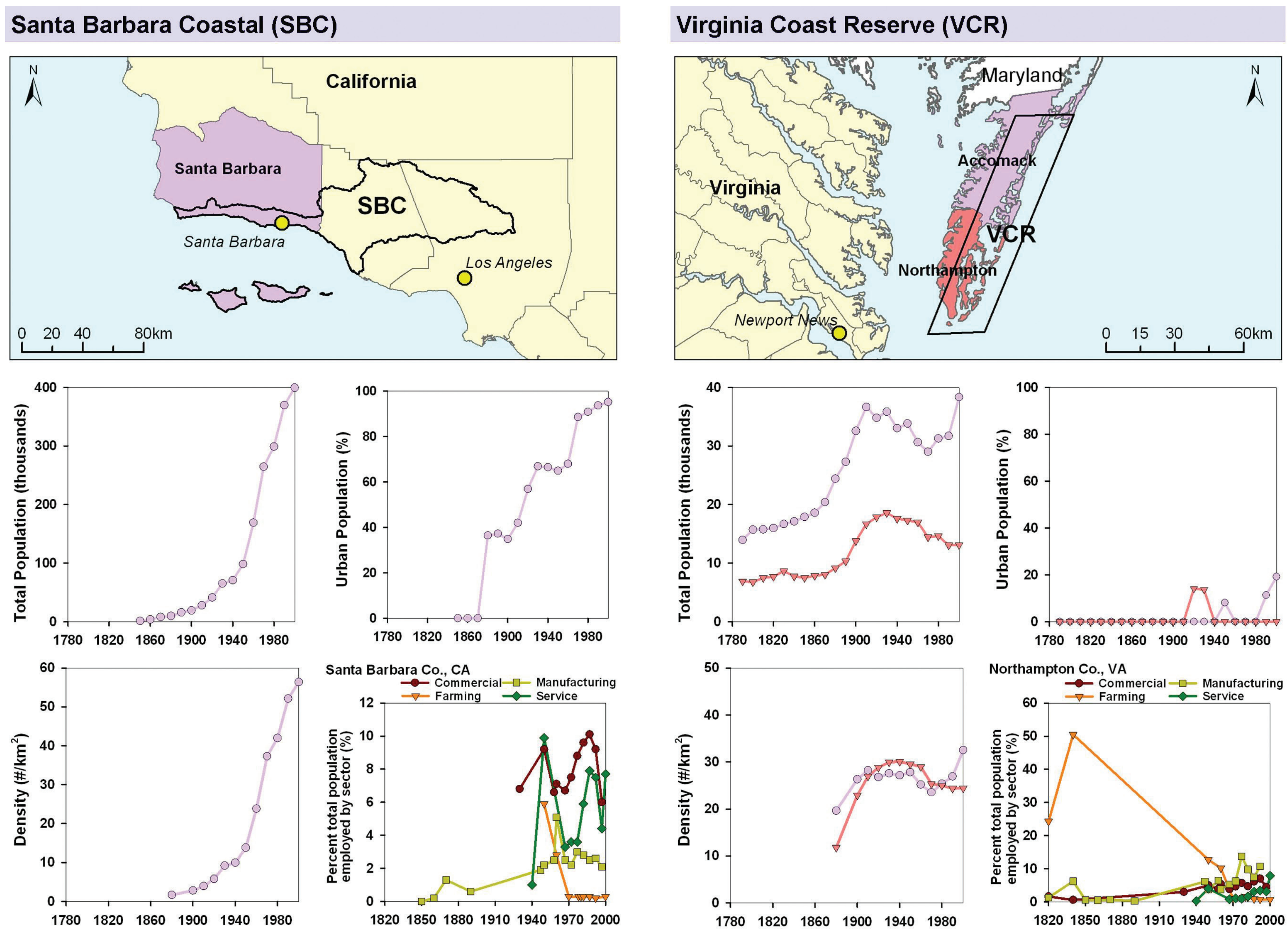


Figure 13-5. Trends for each coastal site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and percentage of total population employed by four sectors in the focal 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.

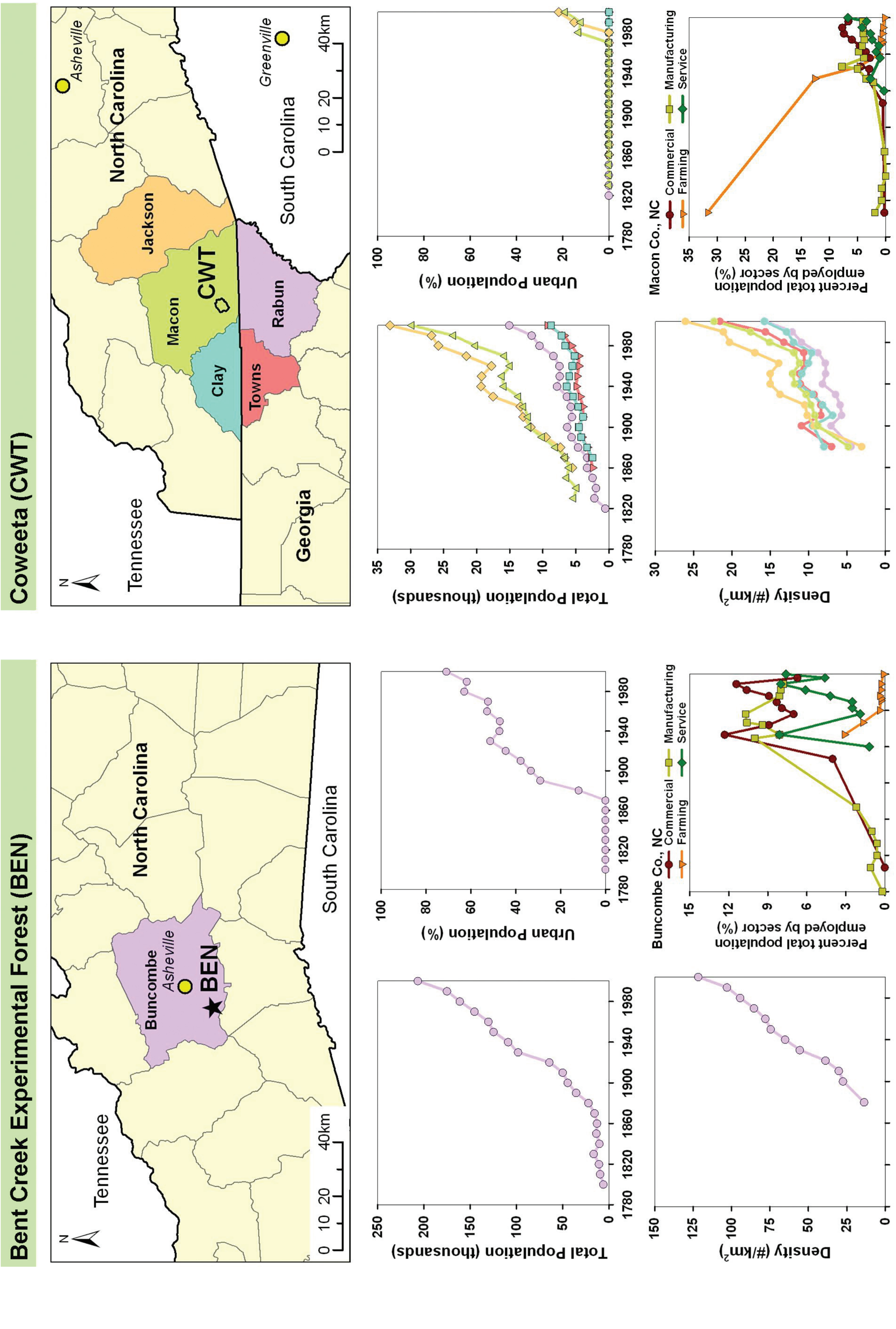
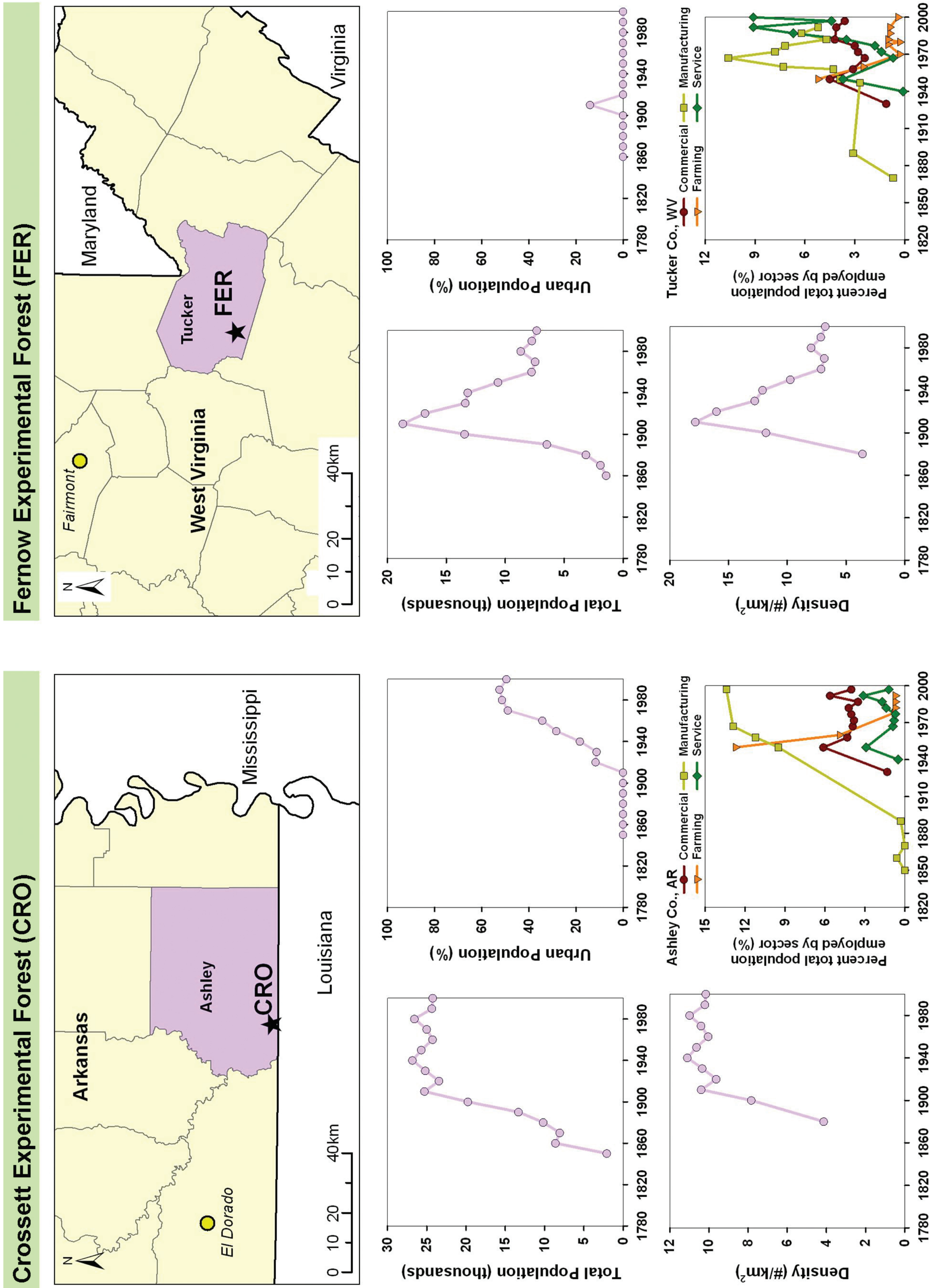


Figure 13-6 (eastern forest sites) continued next page.



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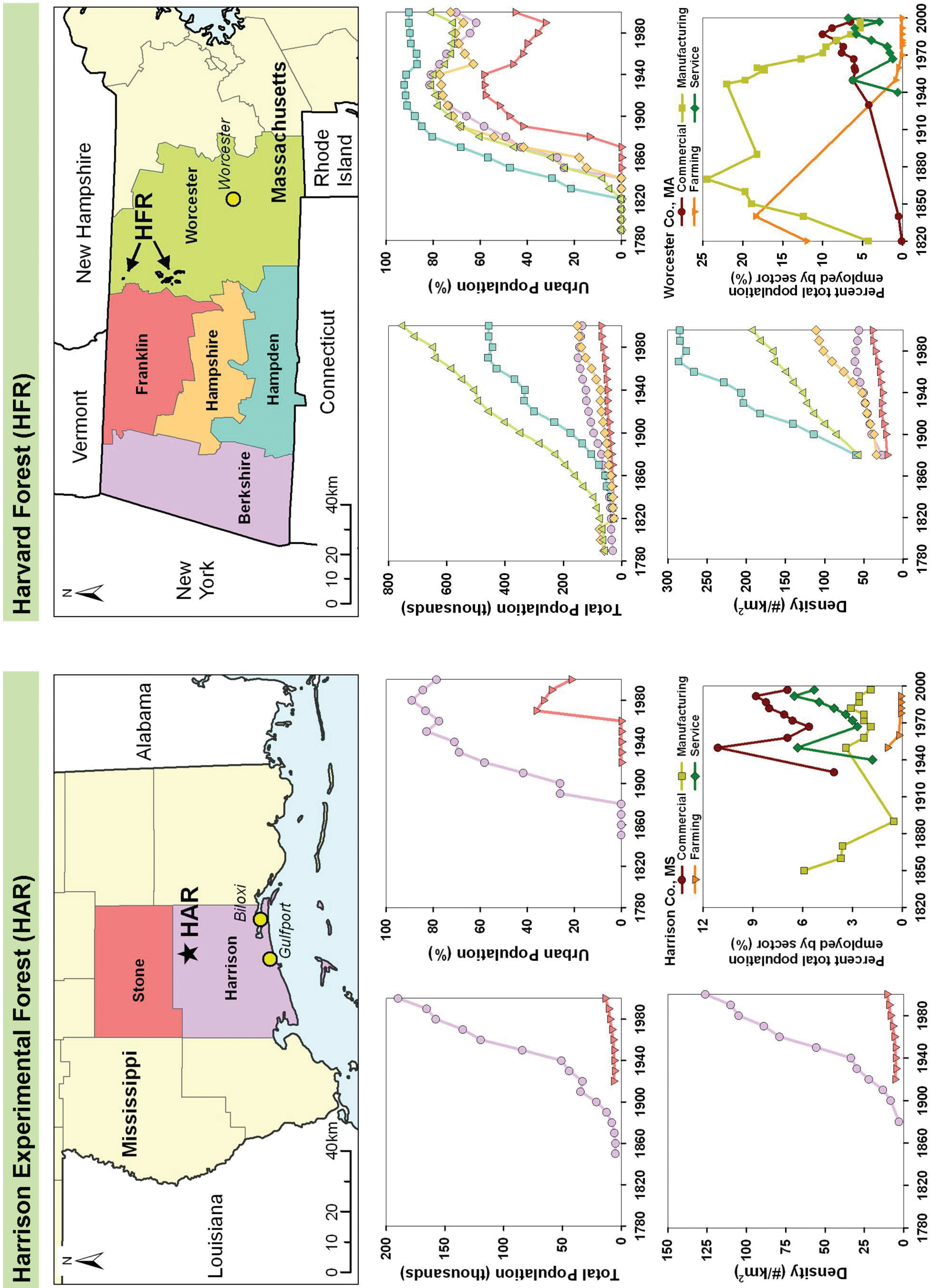

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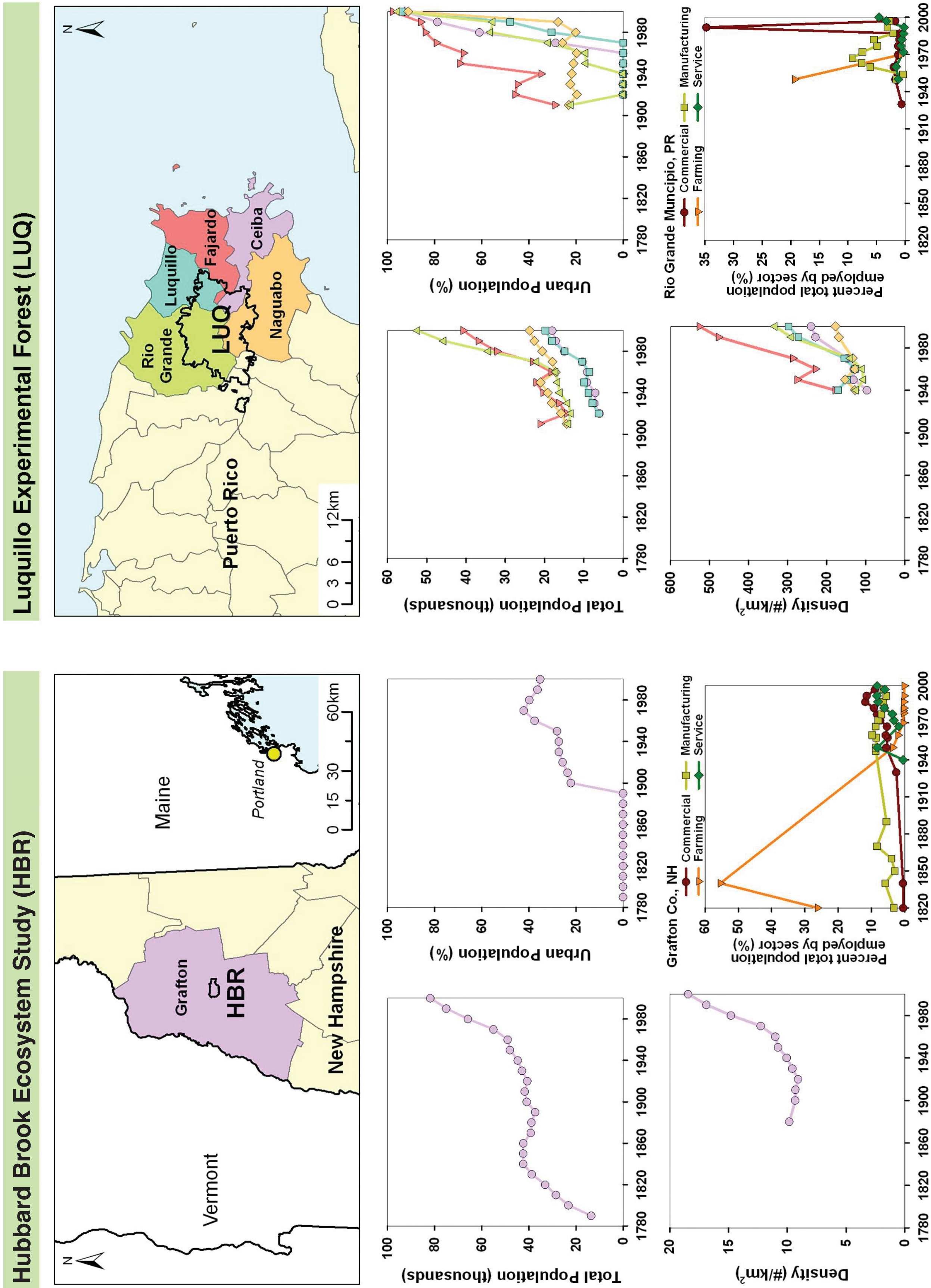

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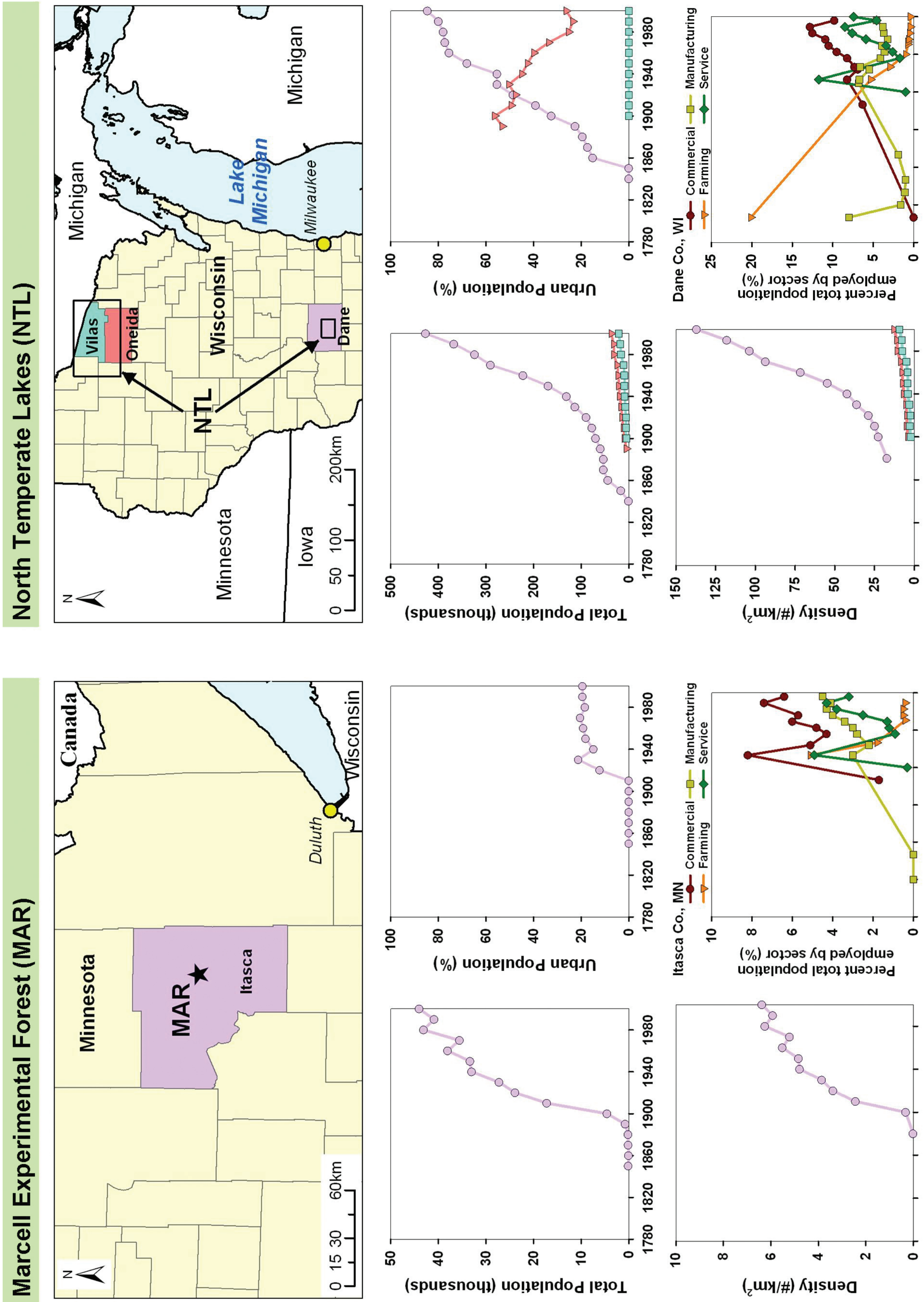

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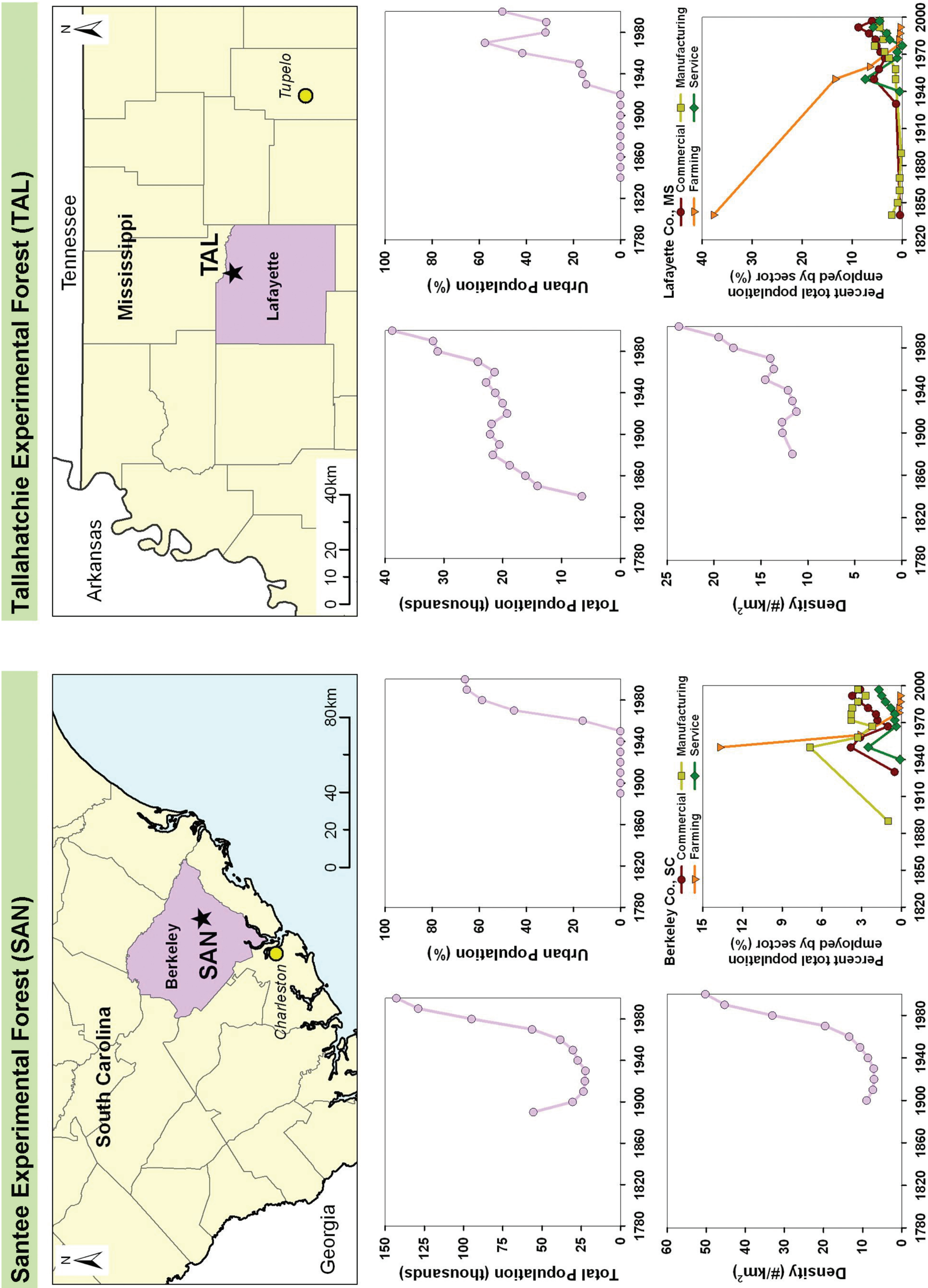

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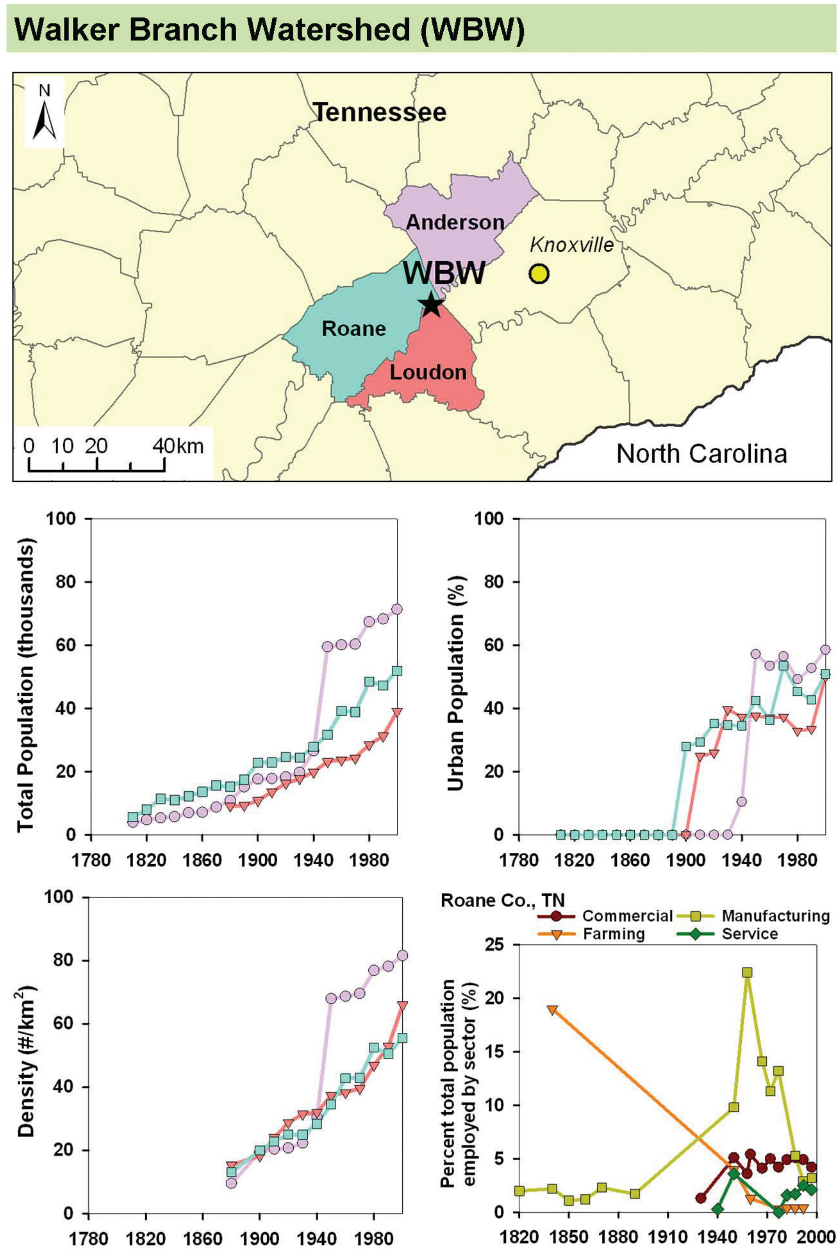


Figure 13-6. Trends for each eastern forest site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and (bottom right) percentage of total population employed by 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.

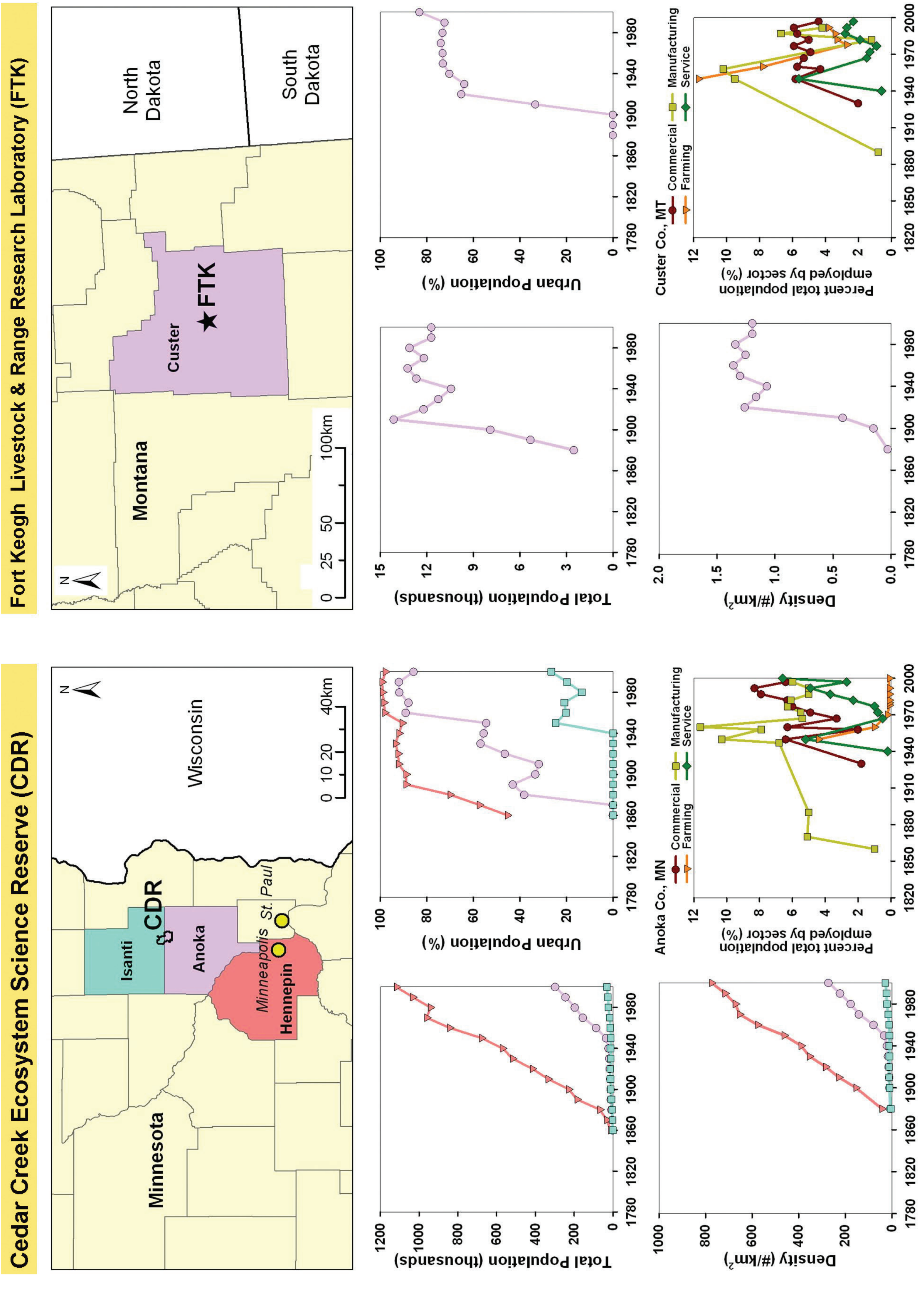
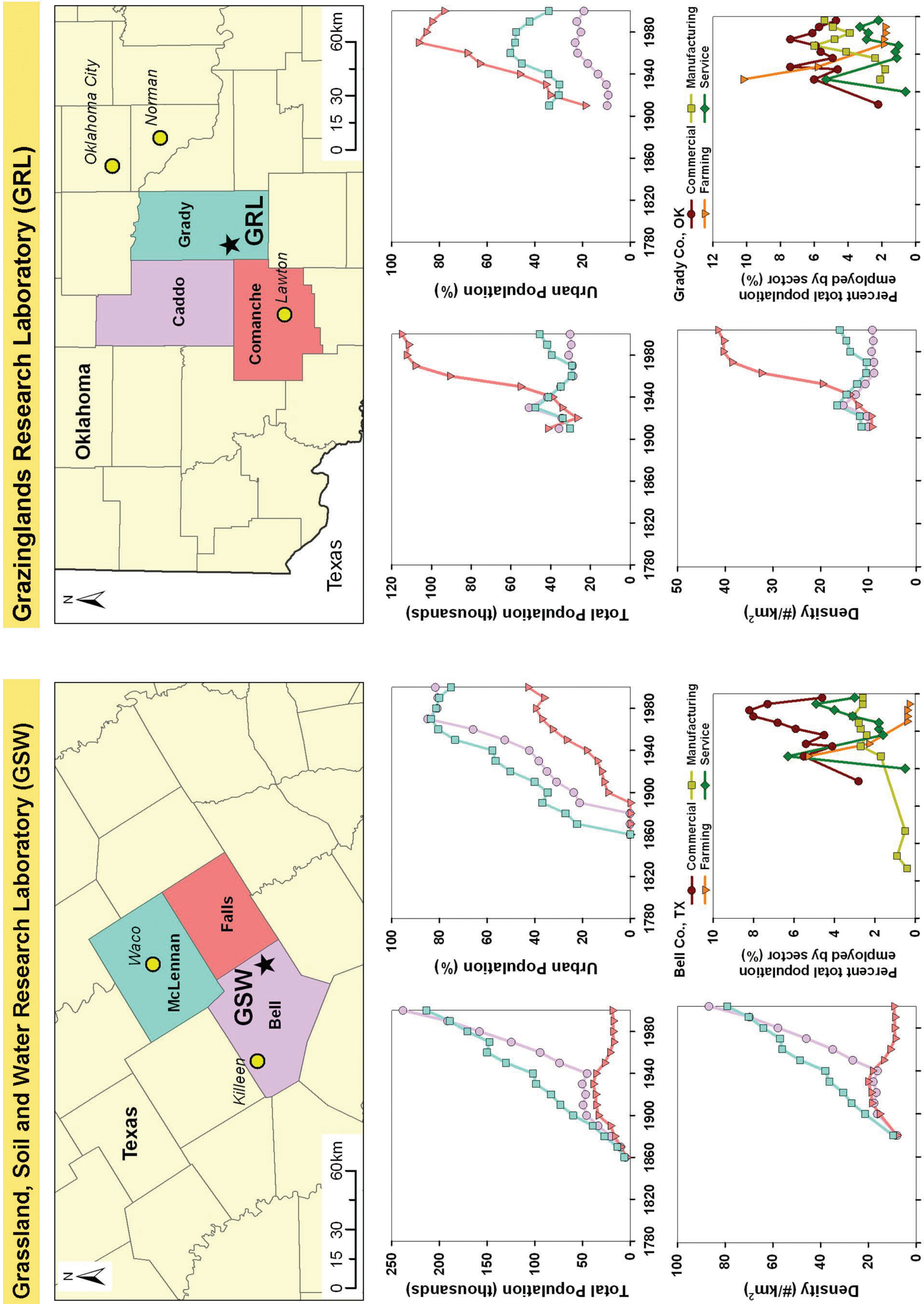


Figure 13-7 (grassland and savanna sites) continued next page.



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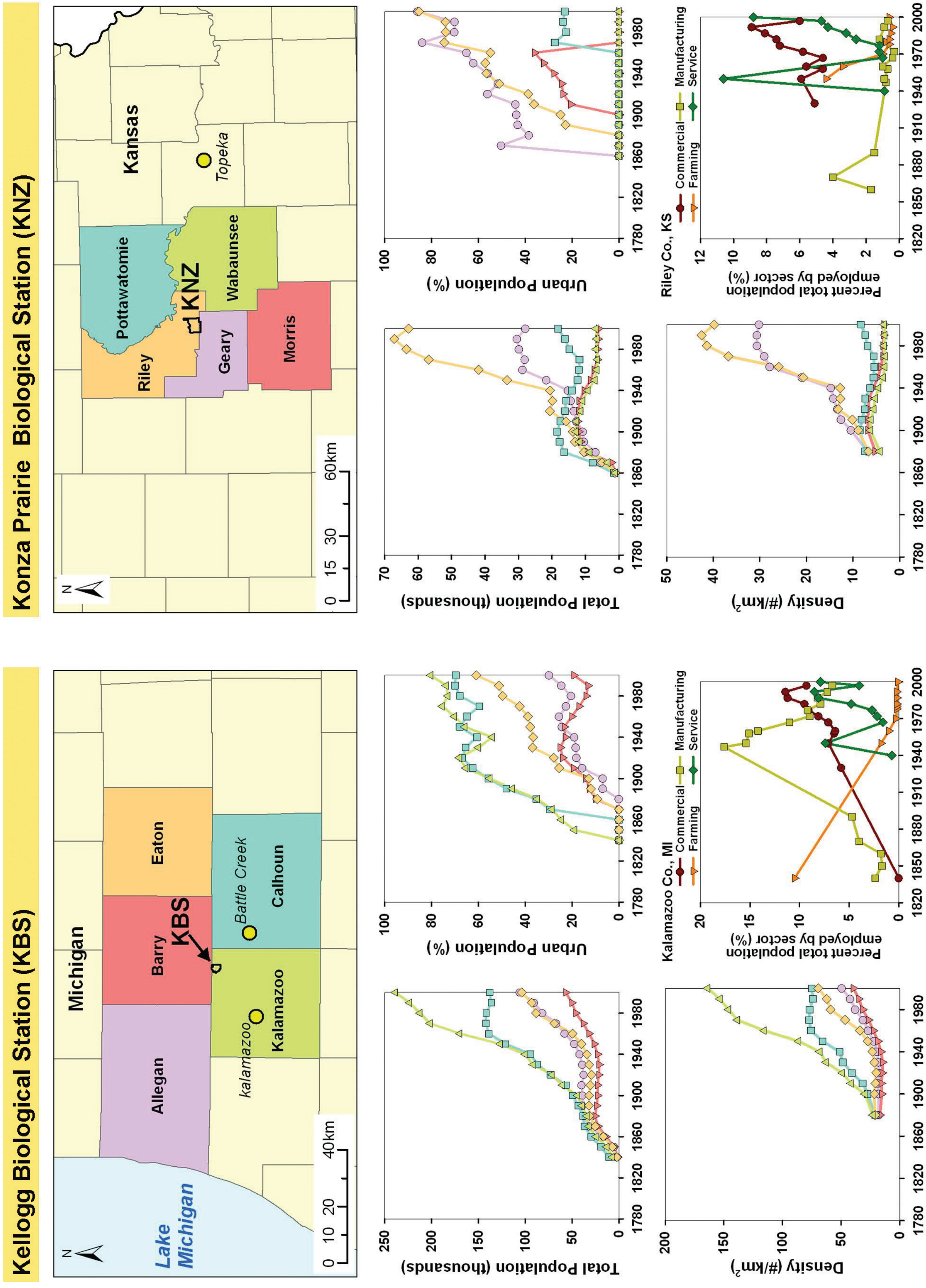

Figure 13-7 (grassland and savanna sites) continued next page.

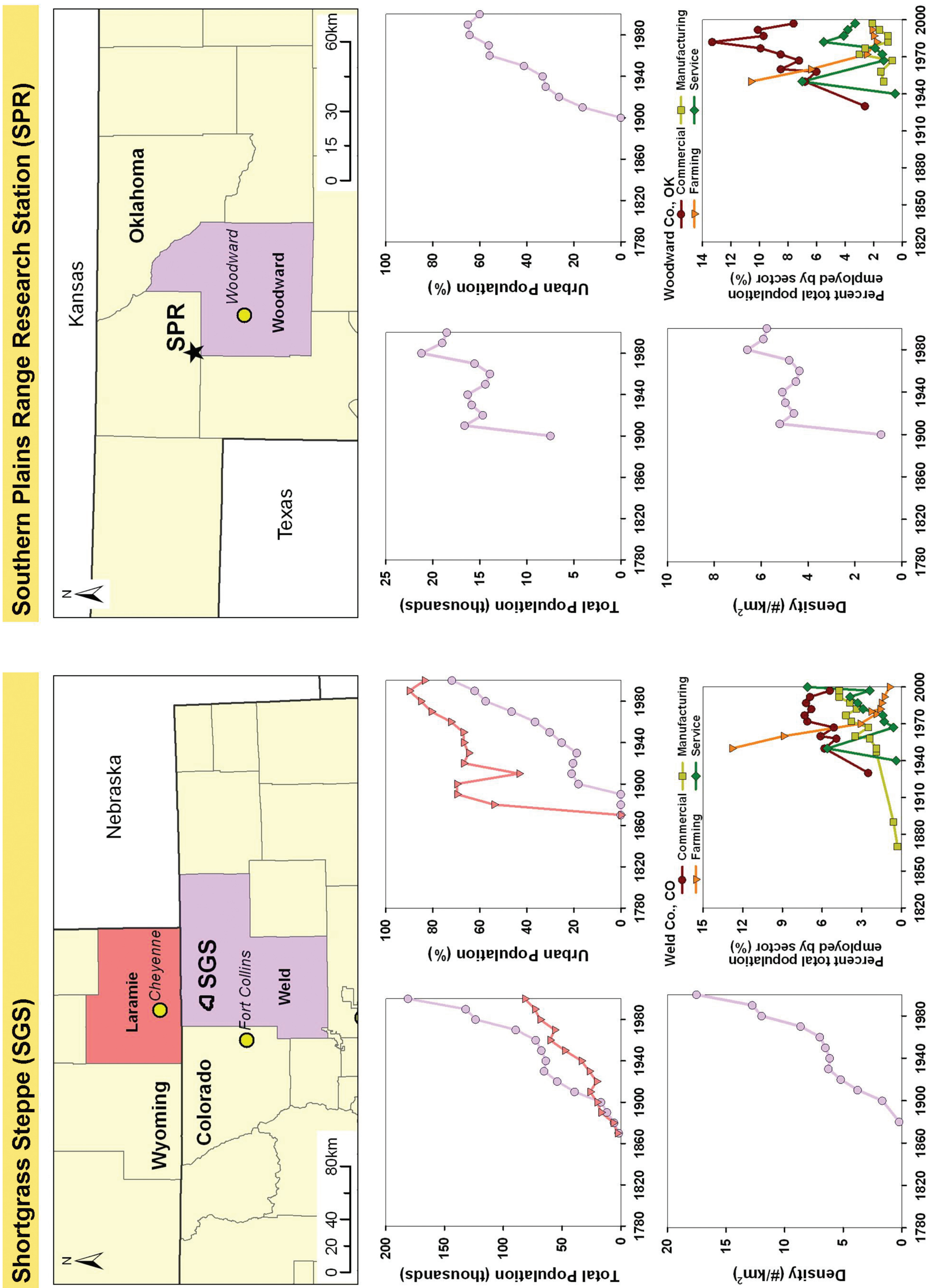

Figure 13-7. Trends for each temperate grassland and savanna site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and percentage of total population employed by 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.

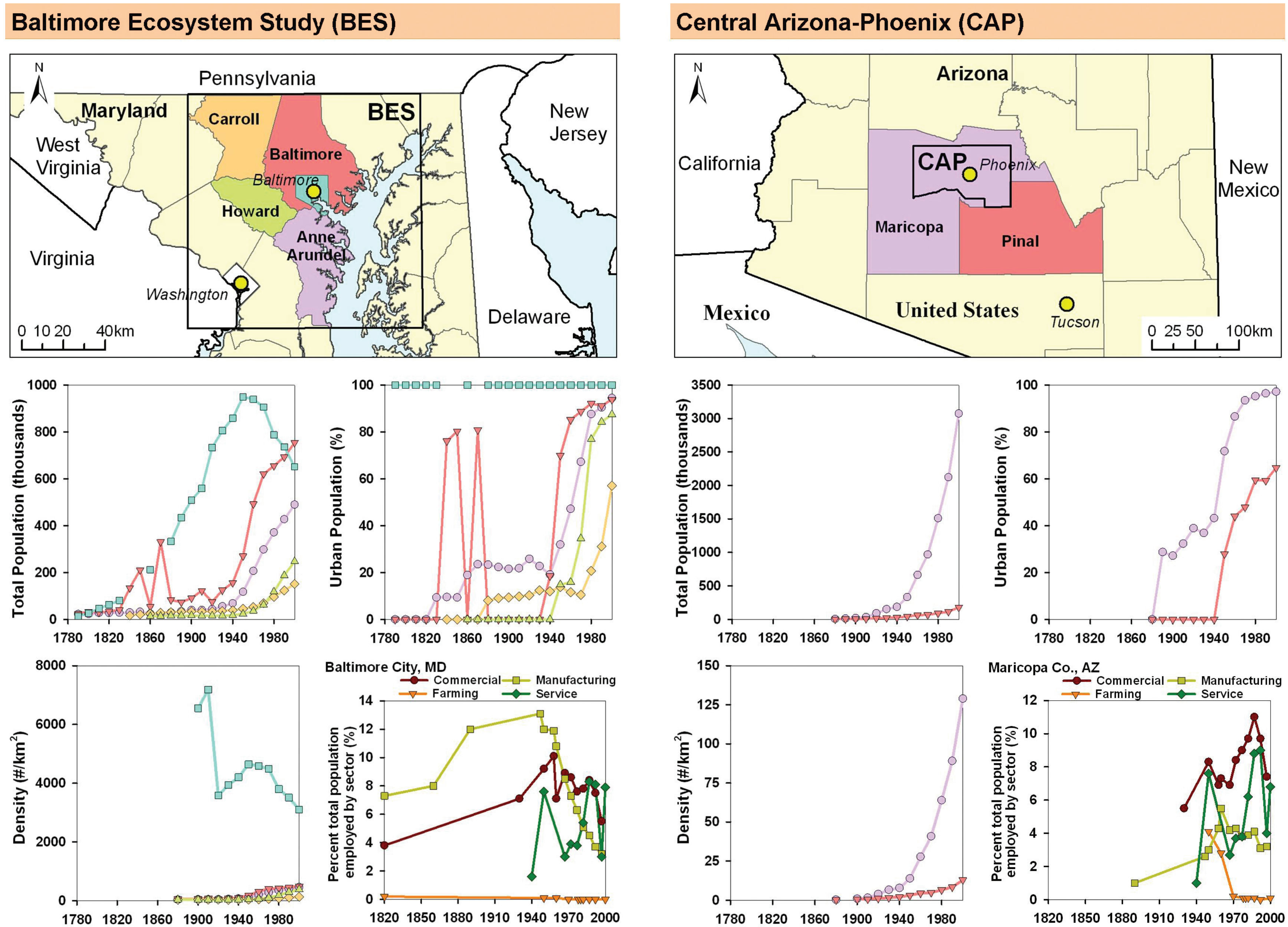

Figure 13-8. Trends for each urban site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and percentage of total population employed by four sectors in the focal 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.

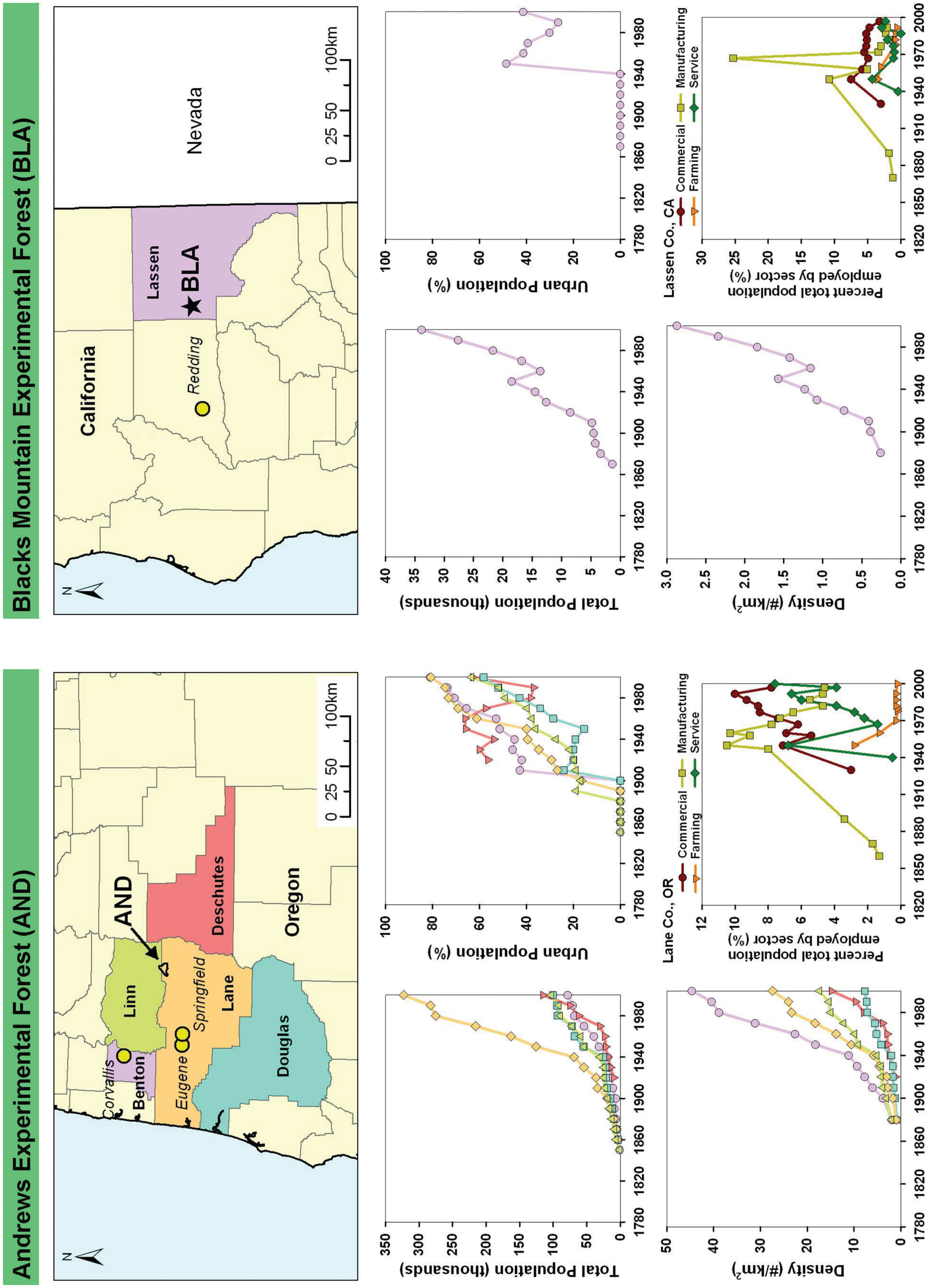

Figure 13-9 (western forest sites) continued next page.

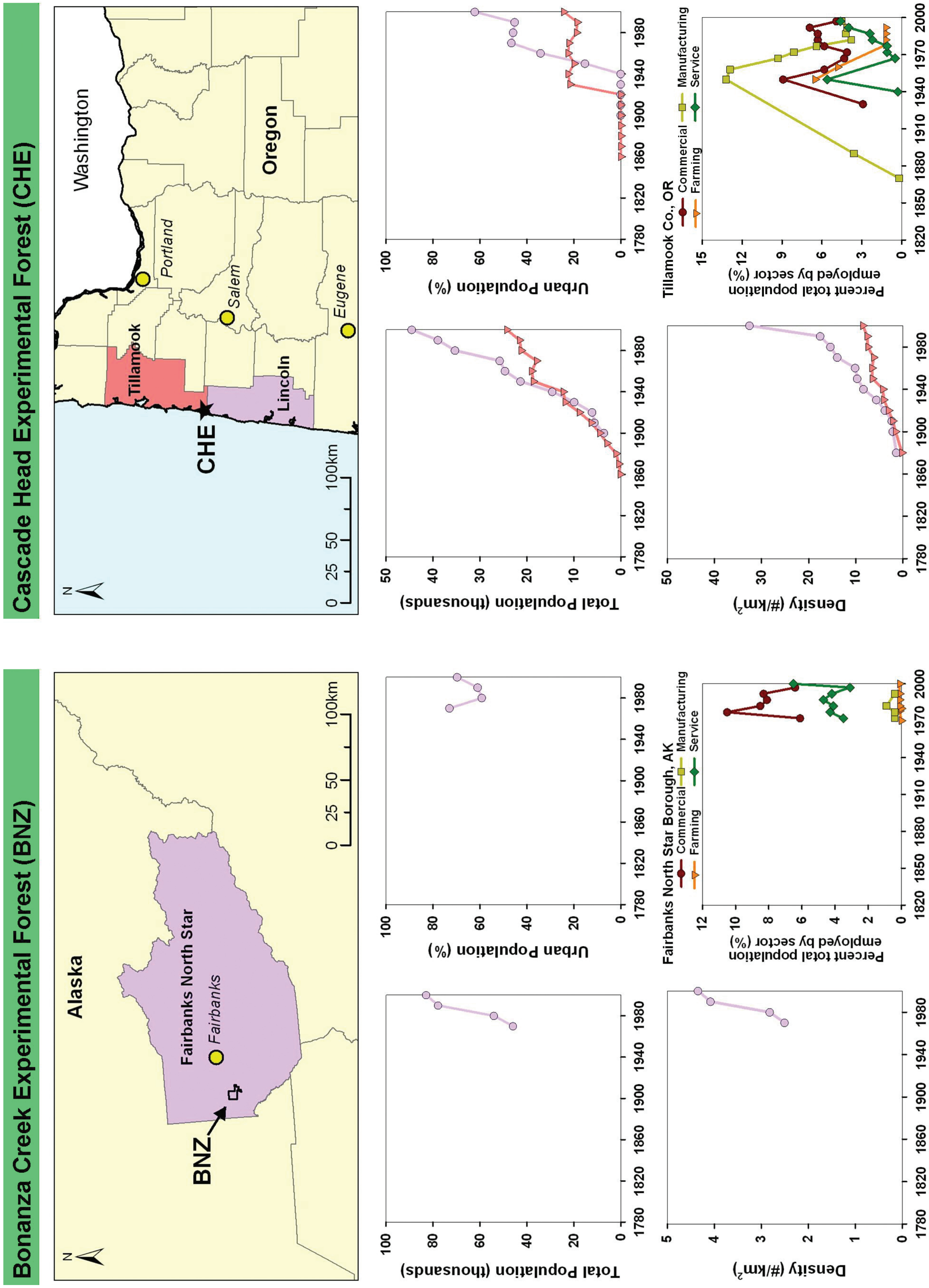

Figure 13-9 (western forest sites) continued next page.

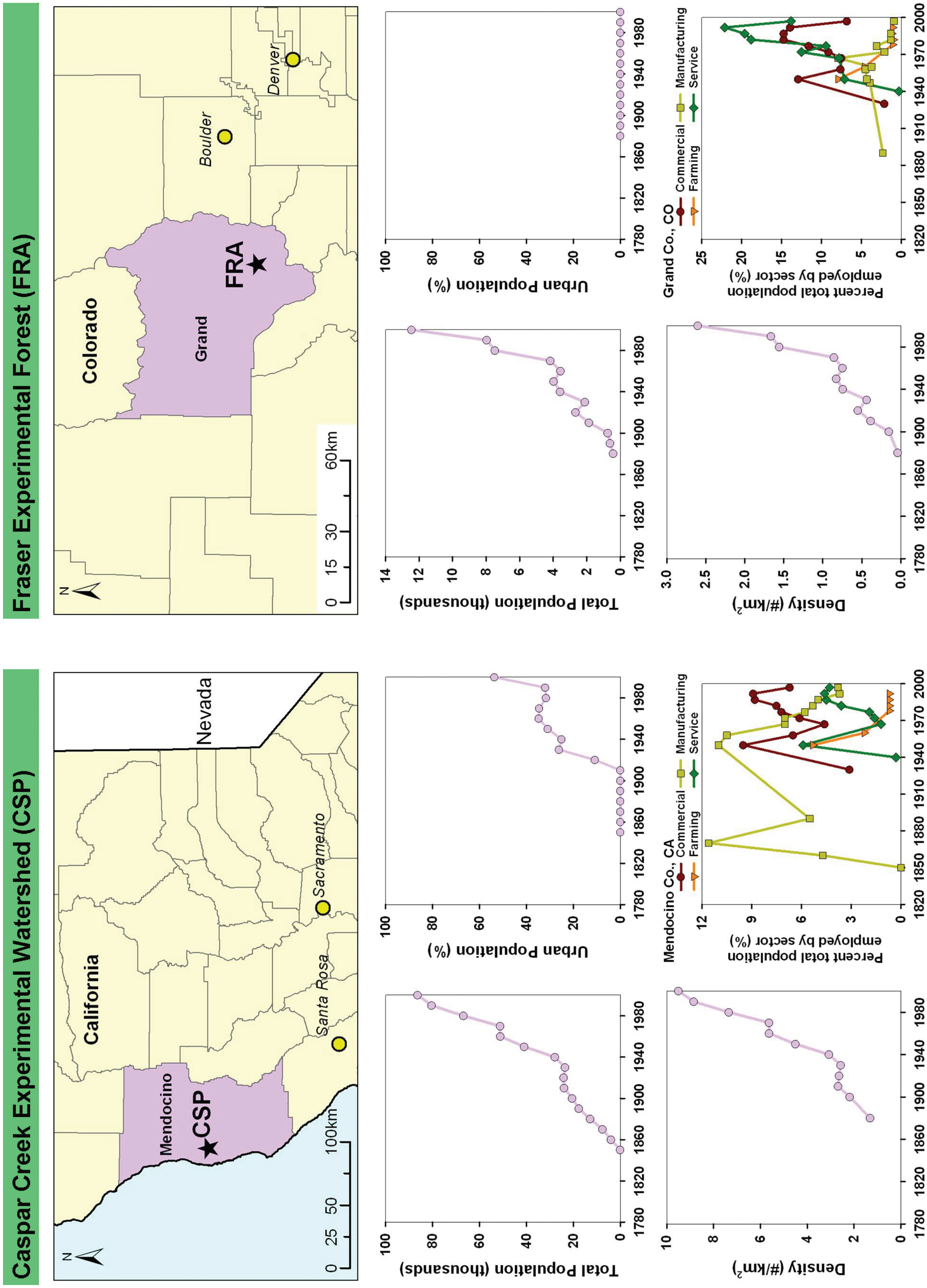

Figure 13-9 (western forest sites) continued next page.

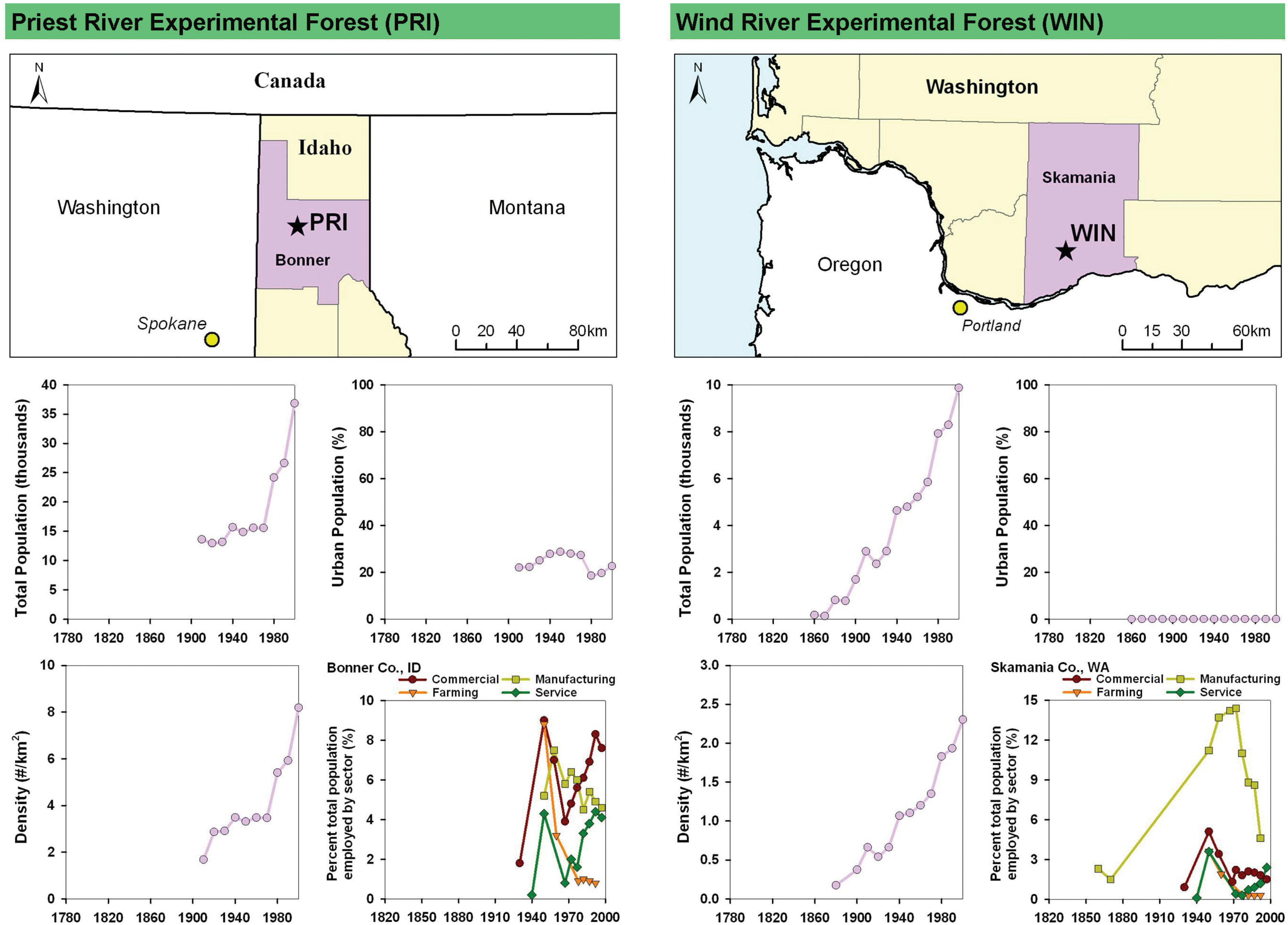

Figure 13-9. Trends for each western forest site: map of counties associated with the site (top), total population size (top left), percentage urban population (top right), and population density (bottom left) in each county for the site; and percentage of total population employed by four sectors in 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.

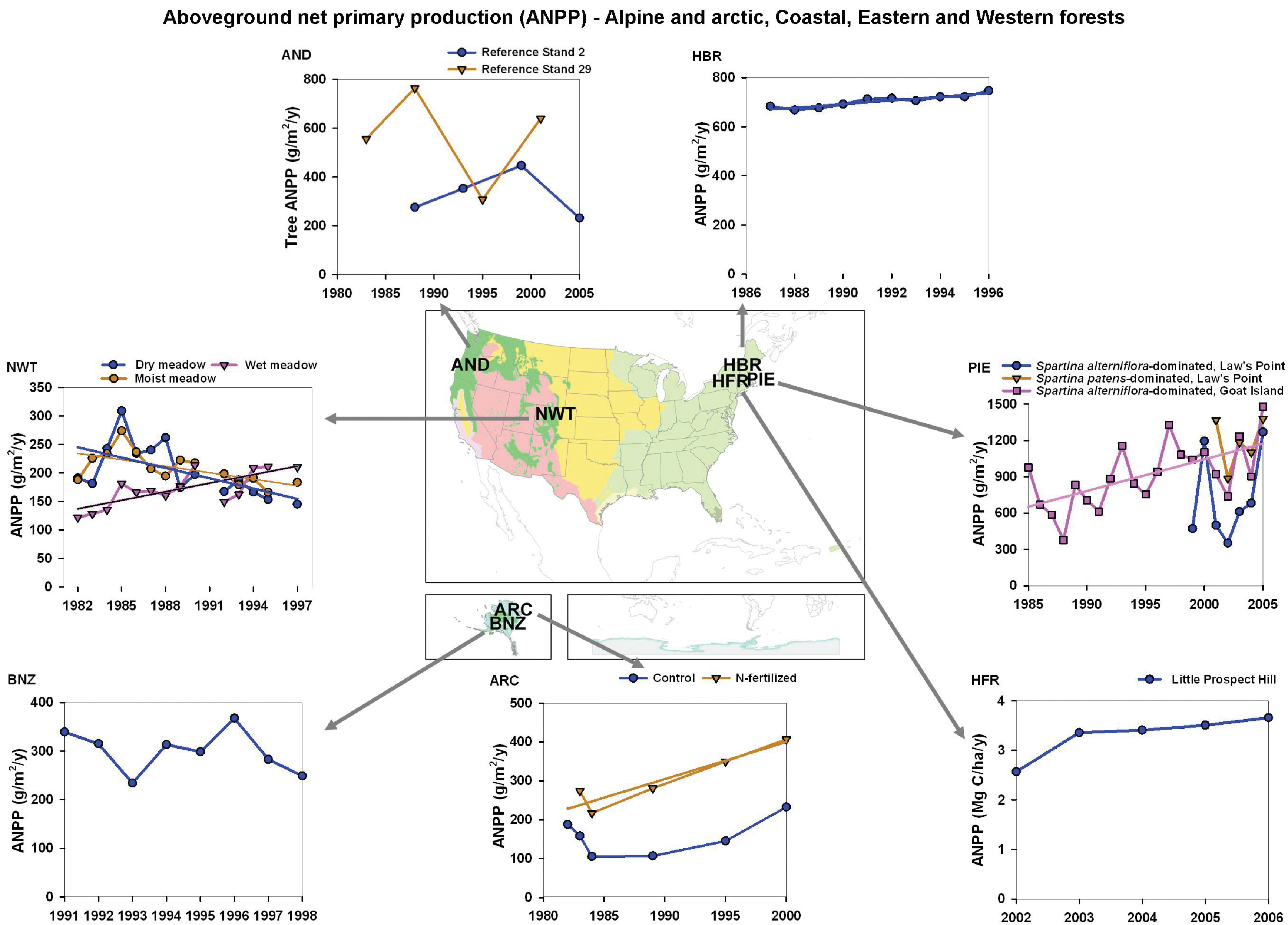

Figure 14-1. Aboveground net primary production (ANPP, g/m²/y or Mg C/ha/y) for arctic and alpine (ARC and NWT), coastal (PIE), and eastern and western forest (AND, BNZ, HBR, and HFR) sites. A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend 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.

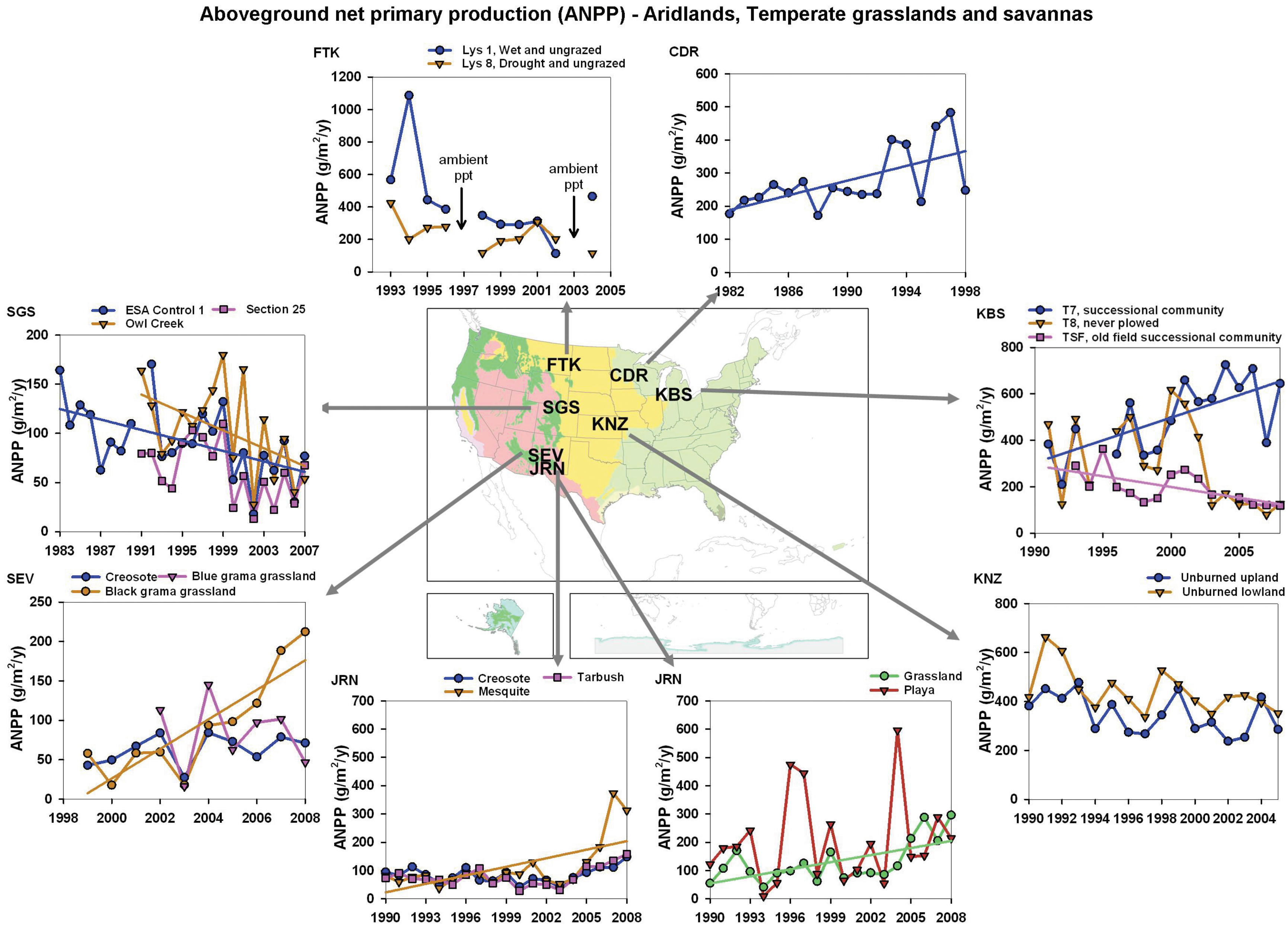

Figure 14-2. Aboveground net primary production (ANPP, g/m²/y) for aridland (FTK, JRN, SEV, and SGS) and temperate grassland/savanna (CDR, KBS, and KNZ) sites. A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant 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.

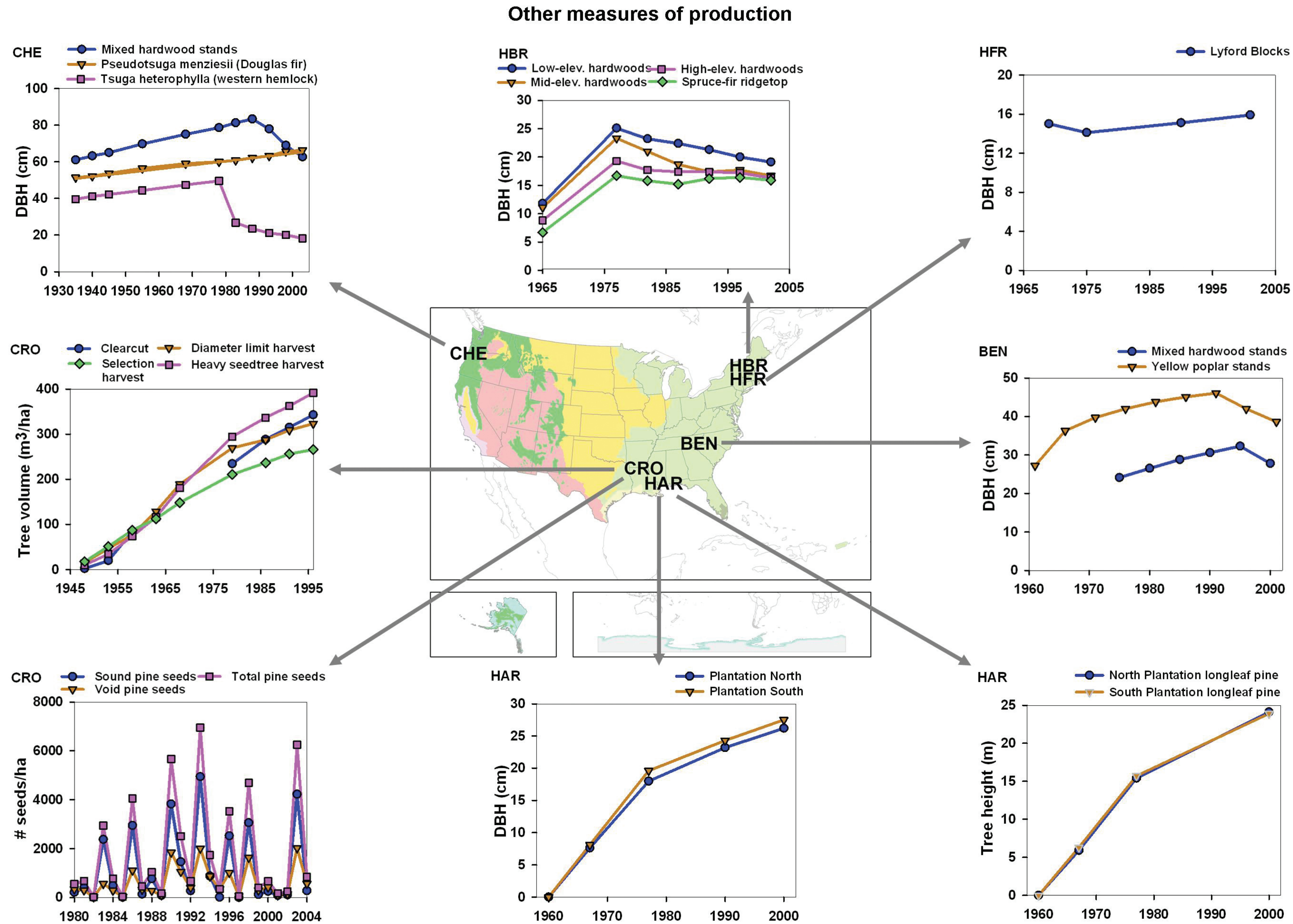

Figure 14-3. Other measures of terrestrial productivity for six forest sites (BEN, CHE, CRO, HAR, HBR, and HFR). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slope is CHE (1). Original data from Internet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

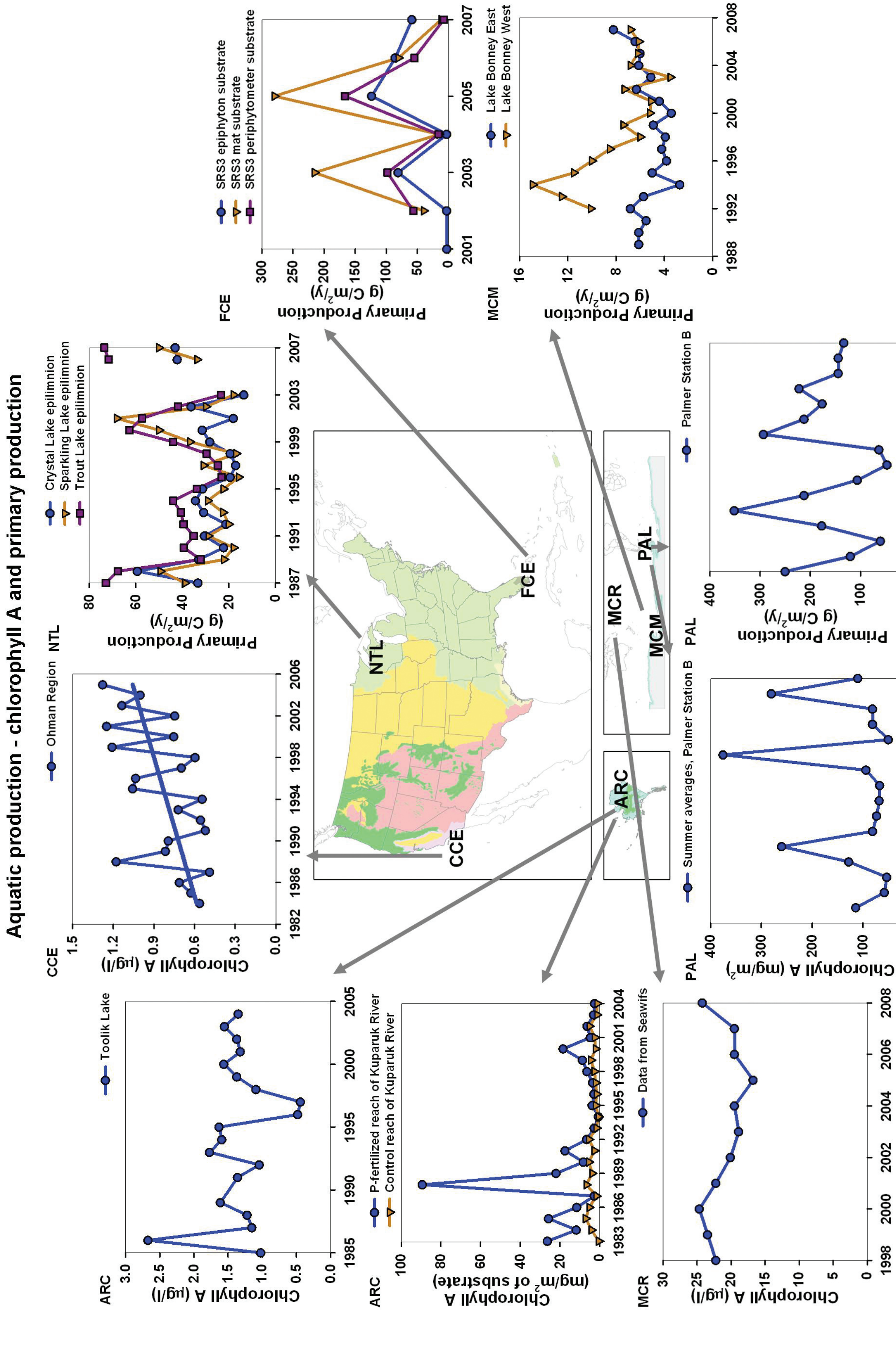

Figure 14-4. Aquatic productivity, either as chlorophyll A (µg/L or mg/m²) or primary production (g C/m²/y) for seven sites (ARC, CCE, FCE, MCM, MCR, NTL, and PAL). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant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

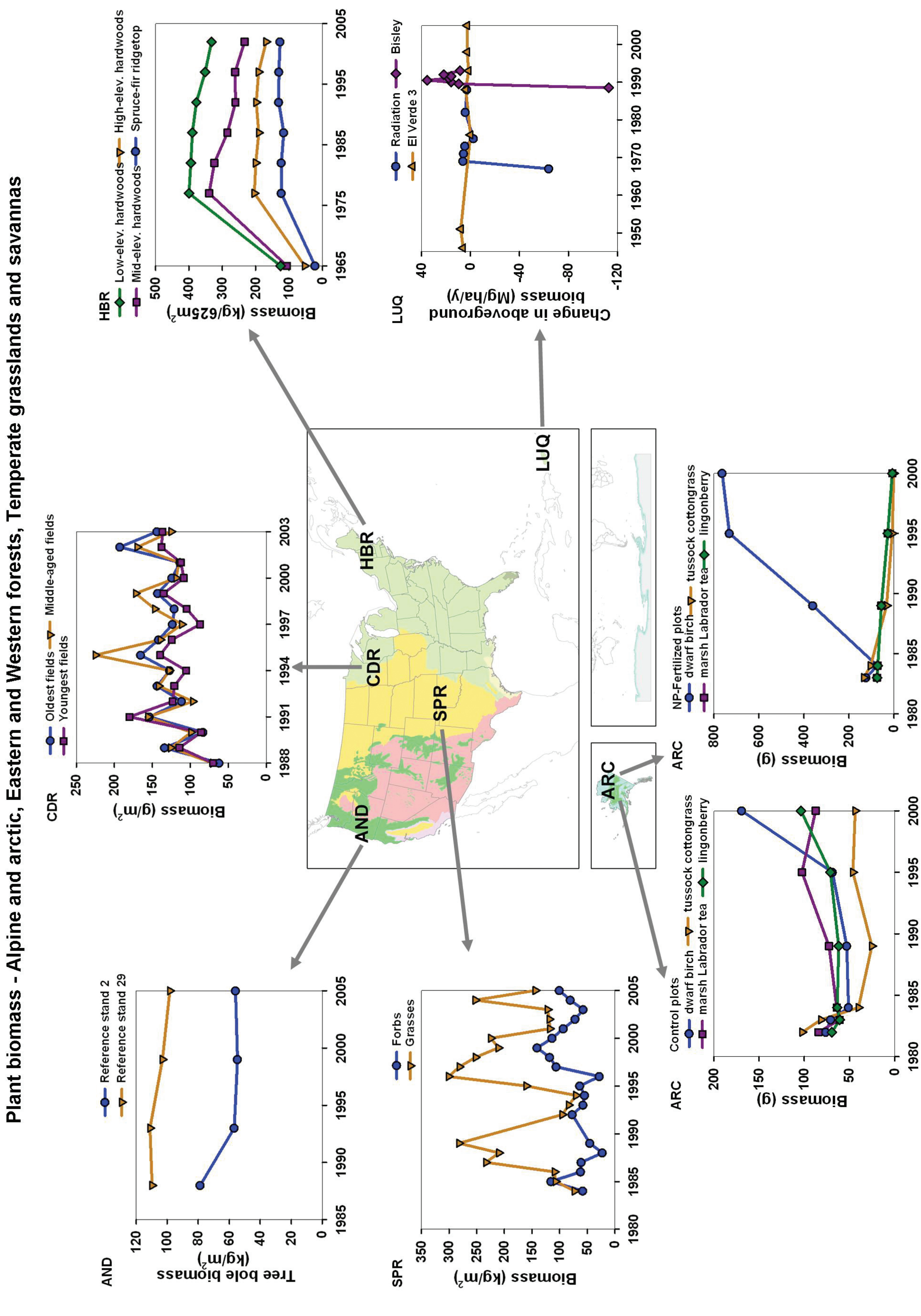

Figure 14-5. Plant biomass for alpine/arctic (ARC), forest (AND and HBR), and grassland (CDR and SPR) sites. See appendix 19 for the taxon/taxa specific to each site. A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. Original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

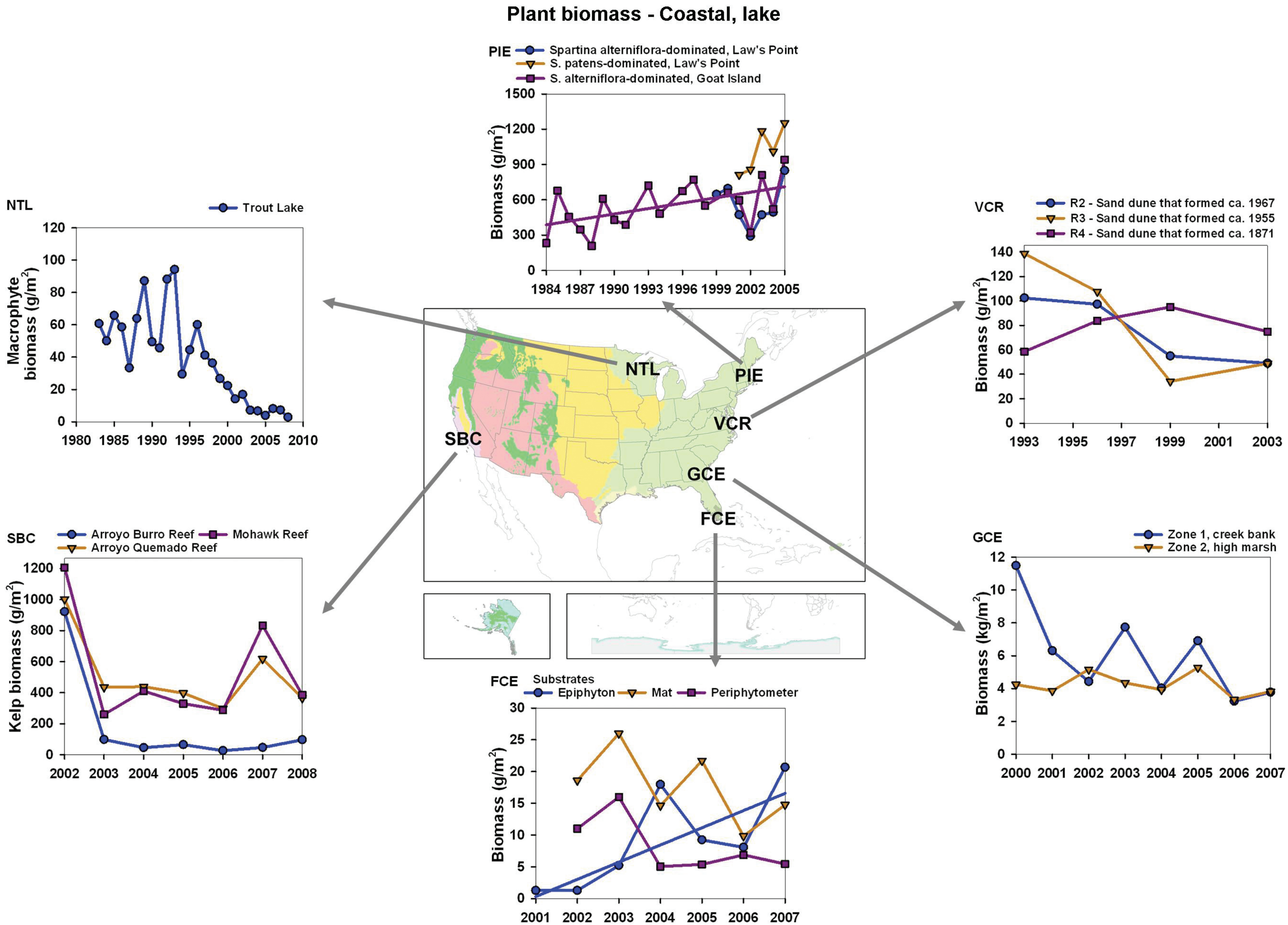

Figure 14-6. Plant biomass (and algae, if noted) for coastal and lake sites (FCE, GCE, NTL, PIE, SBC, and VCR). See appendix 19 for the taxon/taxa specific to each site. A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The 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.

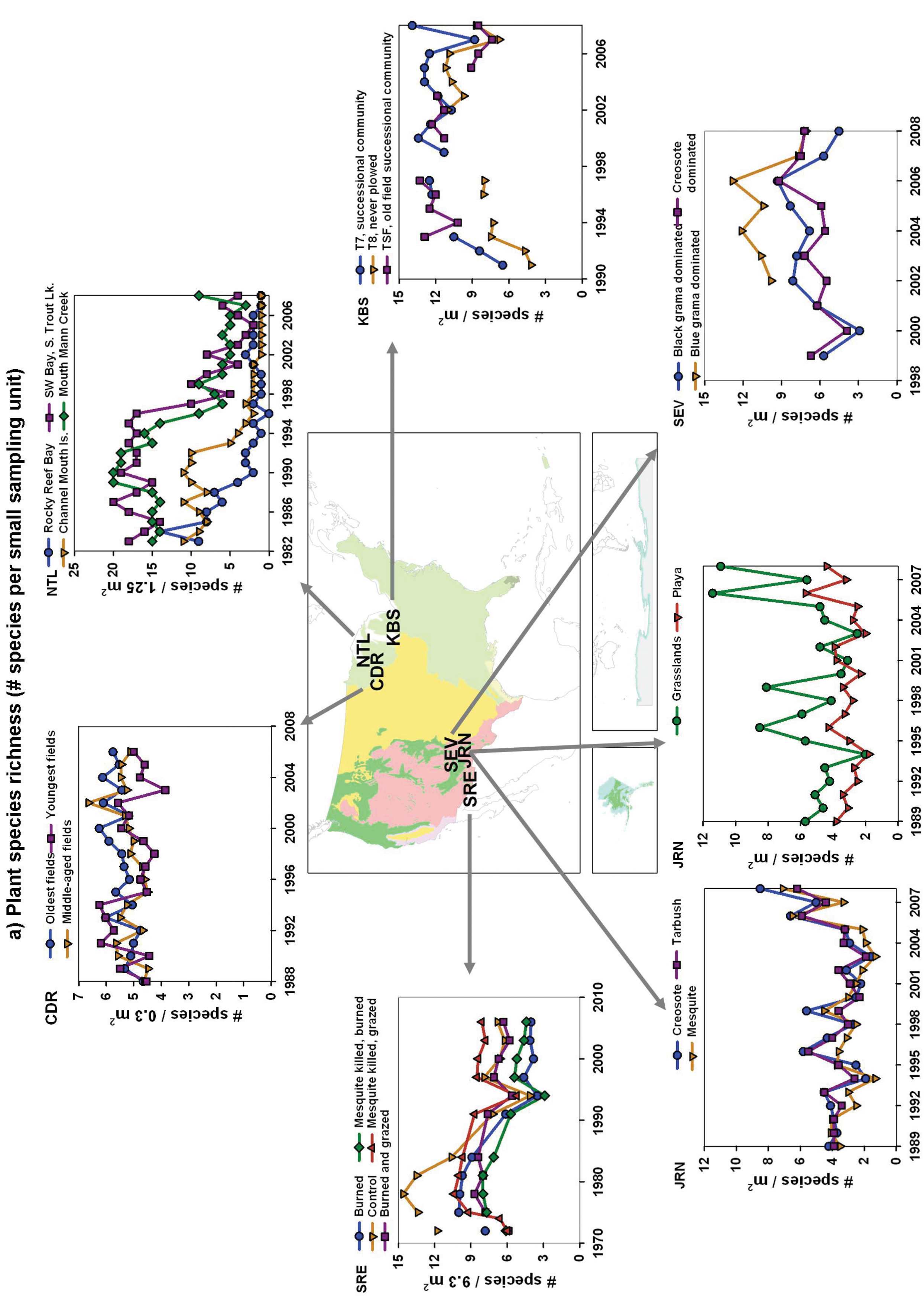

Figure 14-7 continued next page.

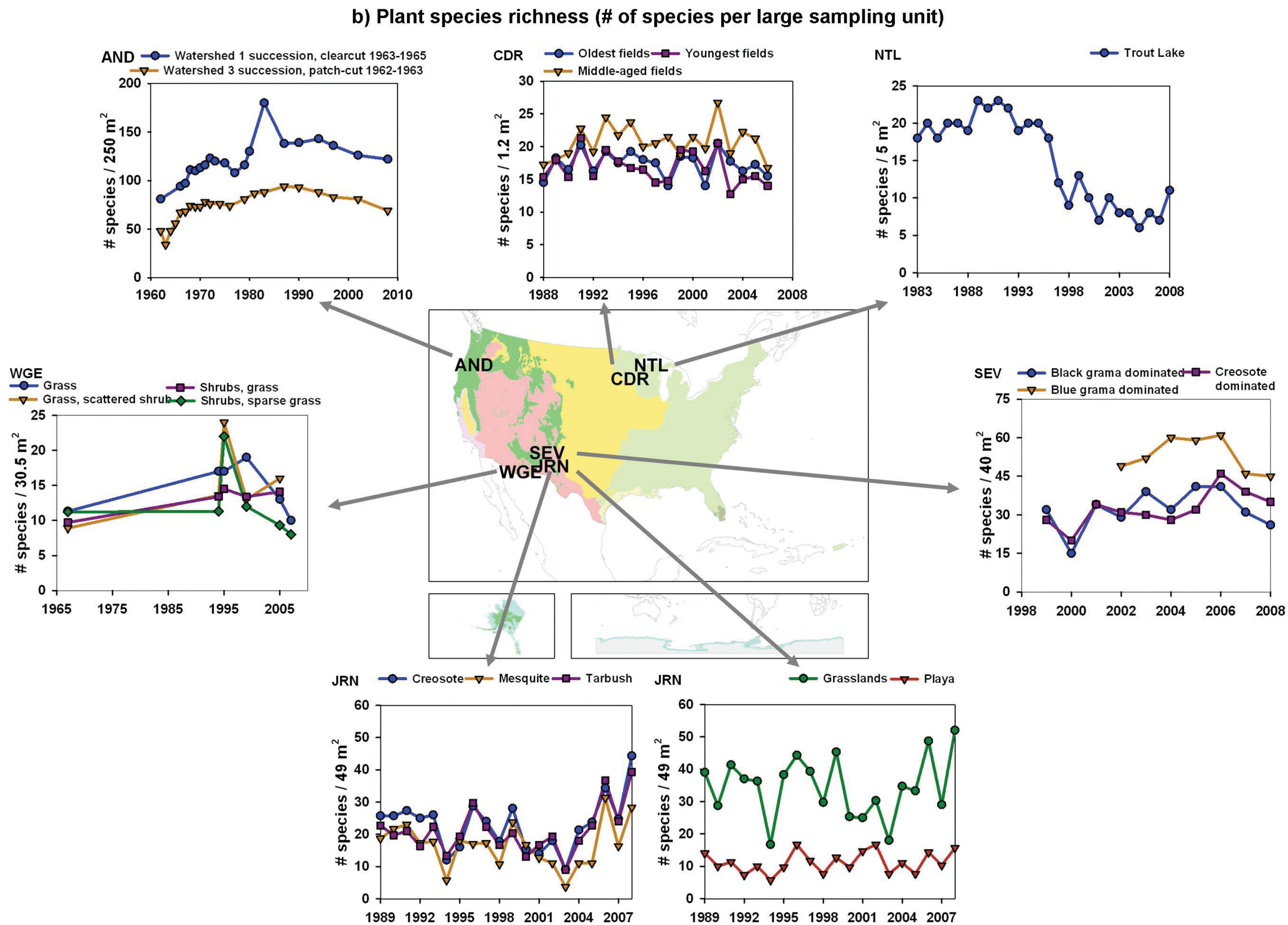

Figure 14-7. Plant species richness for eight sites (AND, CDR, JRN, KBS, NTL, SEV, SRE, and WGE): (a) at small sampling units (0.3-9.3 m²) and (b) at large sampling units (1.2-250 m²). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears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

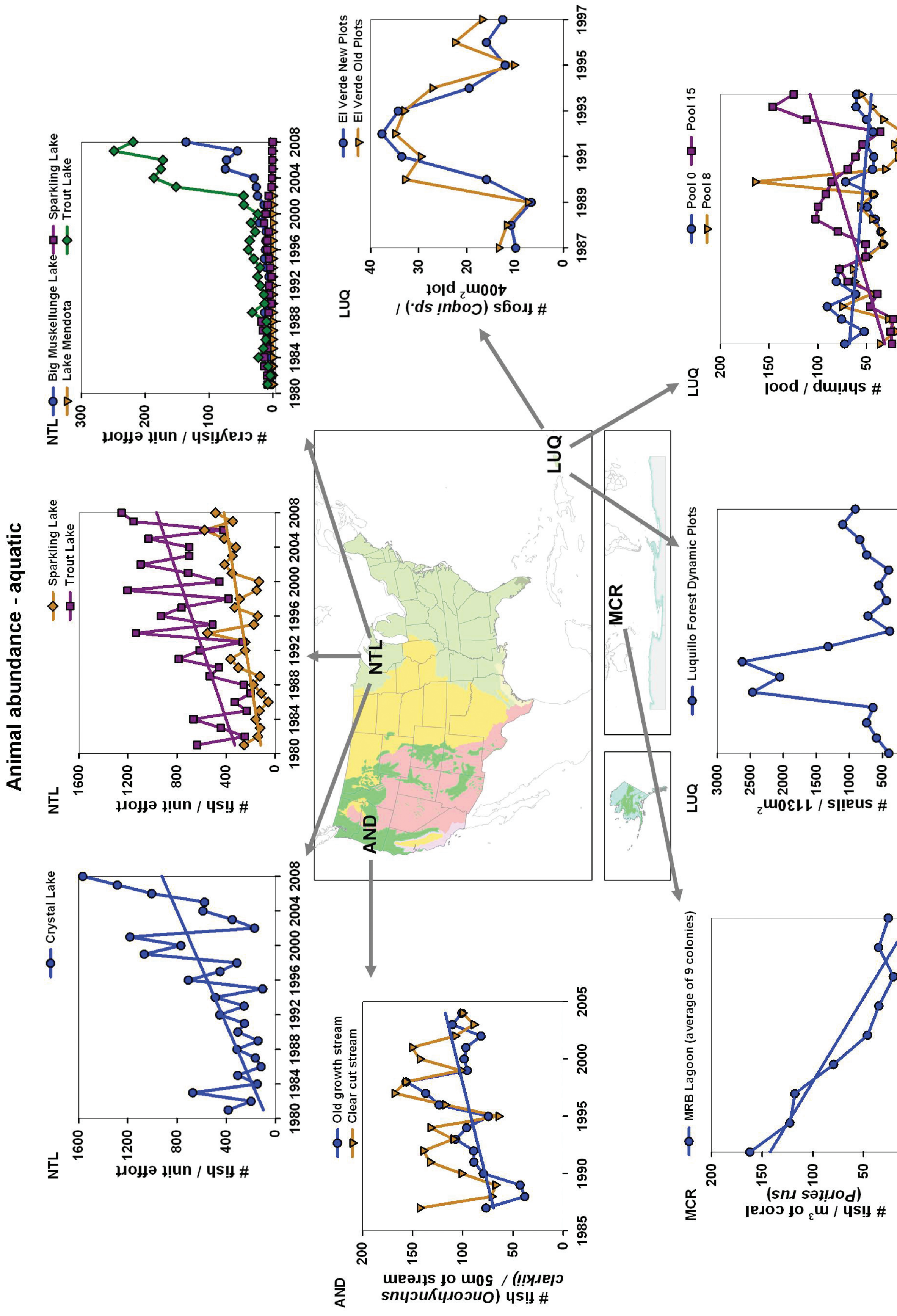

Figure 14-8. Abundance of aquatic animals at four sites (AND, LUQ, MCR, and NTL). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are AND (2), LUQ (-1, 4), MCR (-17), and NTL (11, 24, 31). Original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

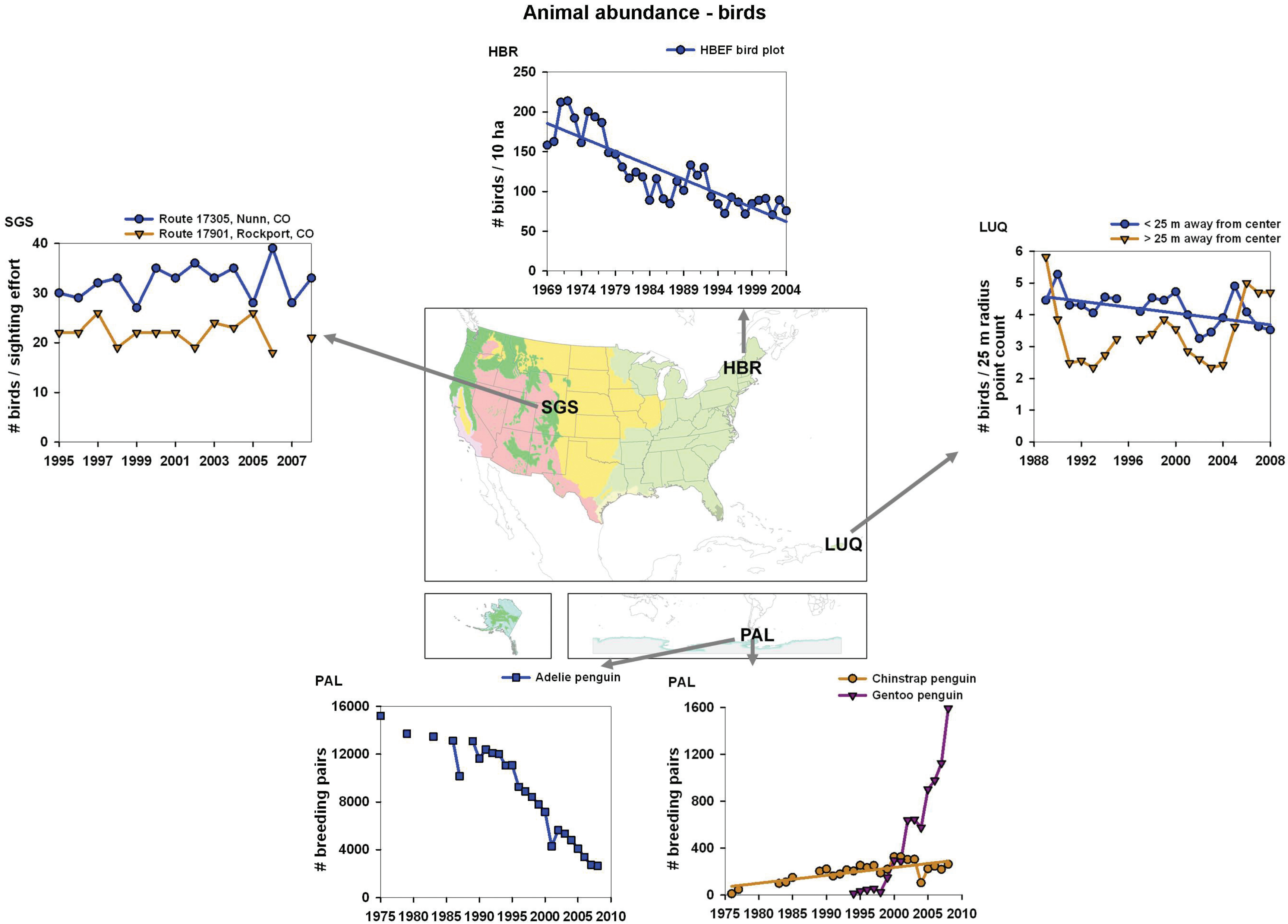

Figure 14-9. Abundance of birds at four sites (HBR, LUQ, PAL, and SGS,). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are HBR (-3.53), LUQ (-0.05), and PAL (6.70). Original data from Internet home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

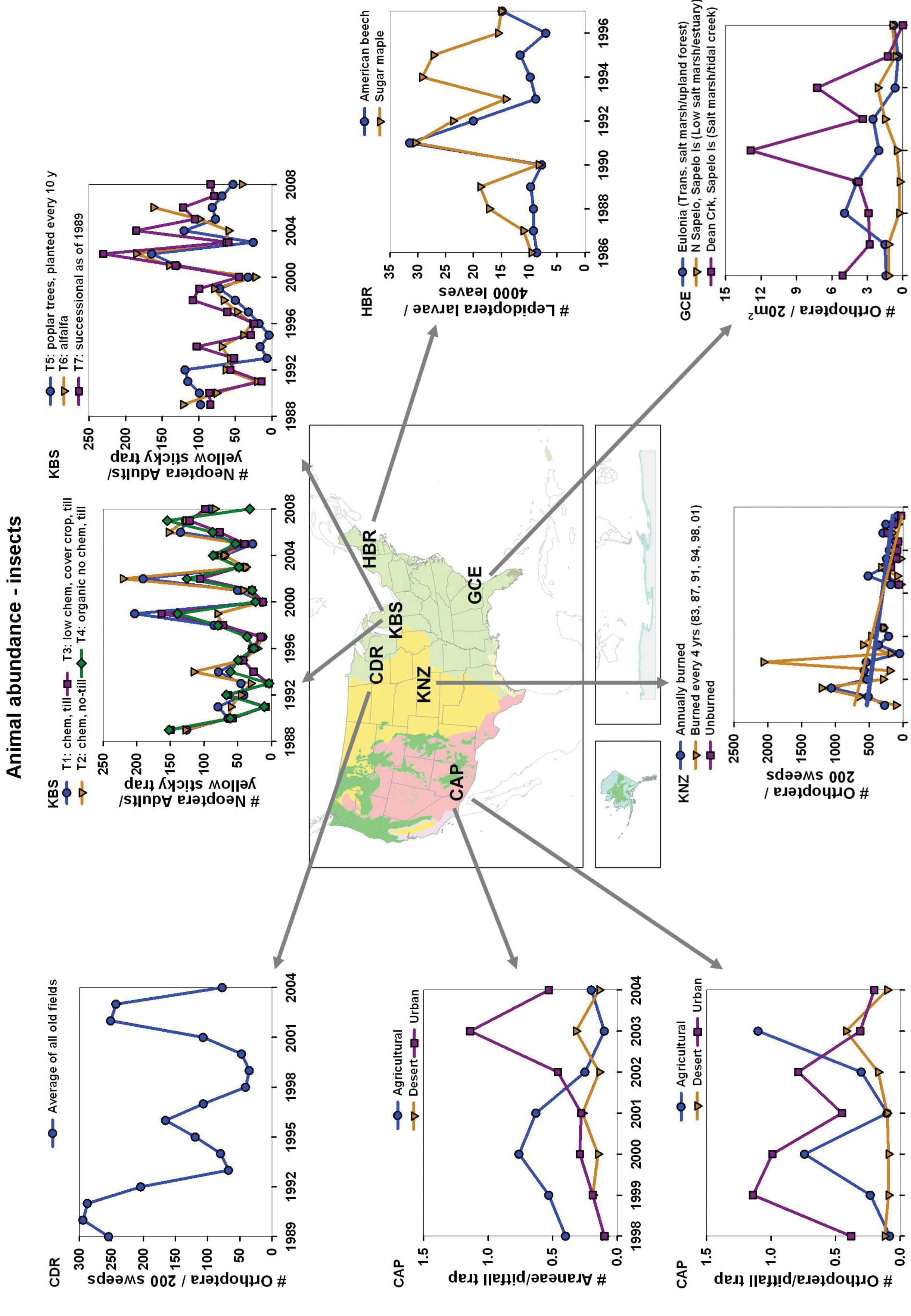

Figure 14-10. Abundance of insects at six sites (CAP, CDR, GCE, HBR, KBS, and KNZ). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are KNZ (-18, -32). Original data from Internet home pages (see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

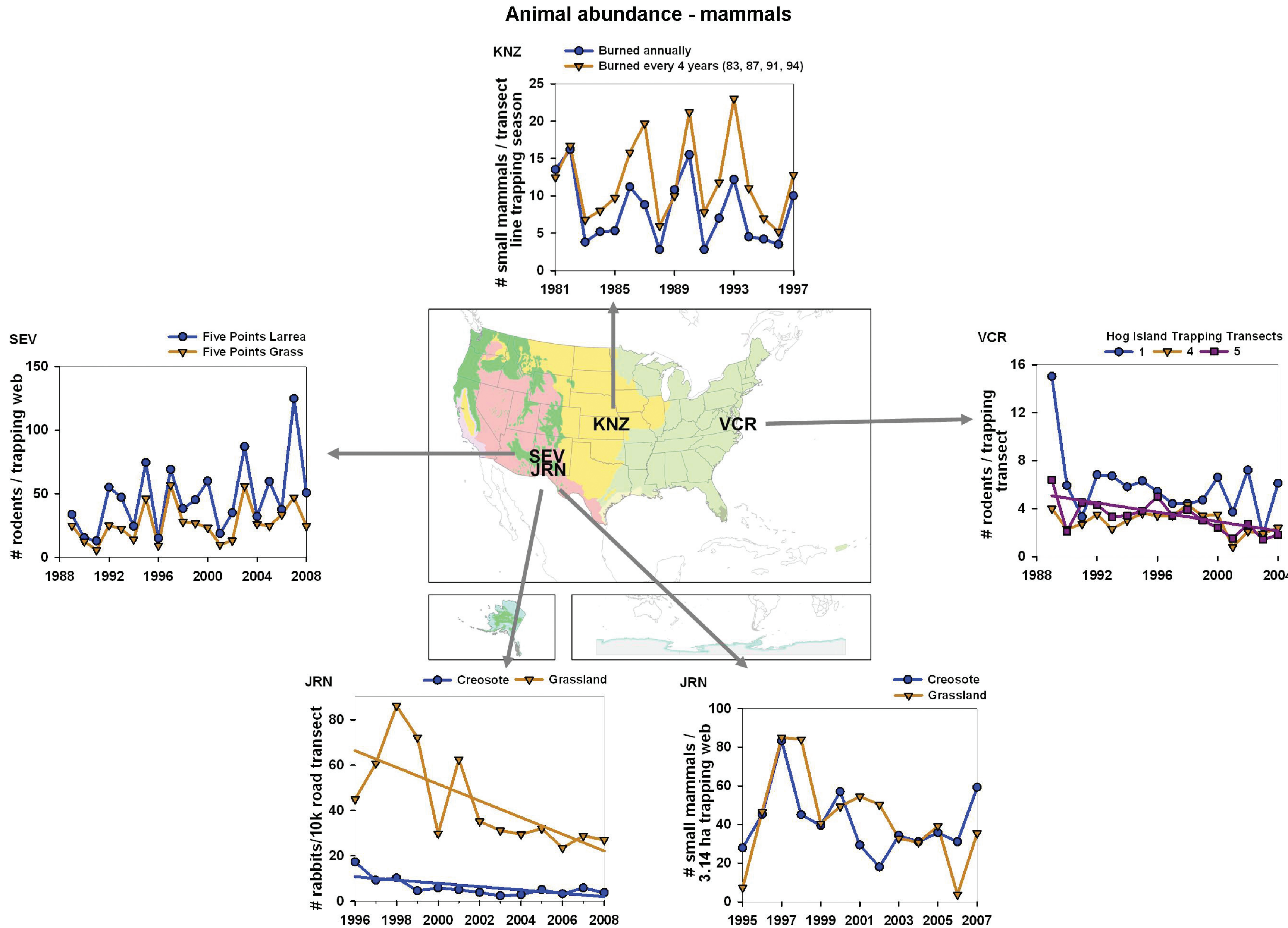

Figure 14-11. Abundance of mammals at four sites (JRN, KNZ, SEV, and VCR). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are JRN (-0.7, -3.7) and VCR (-0.2). Original data from Internet home pages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

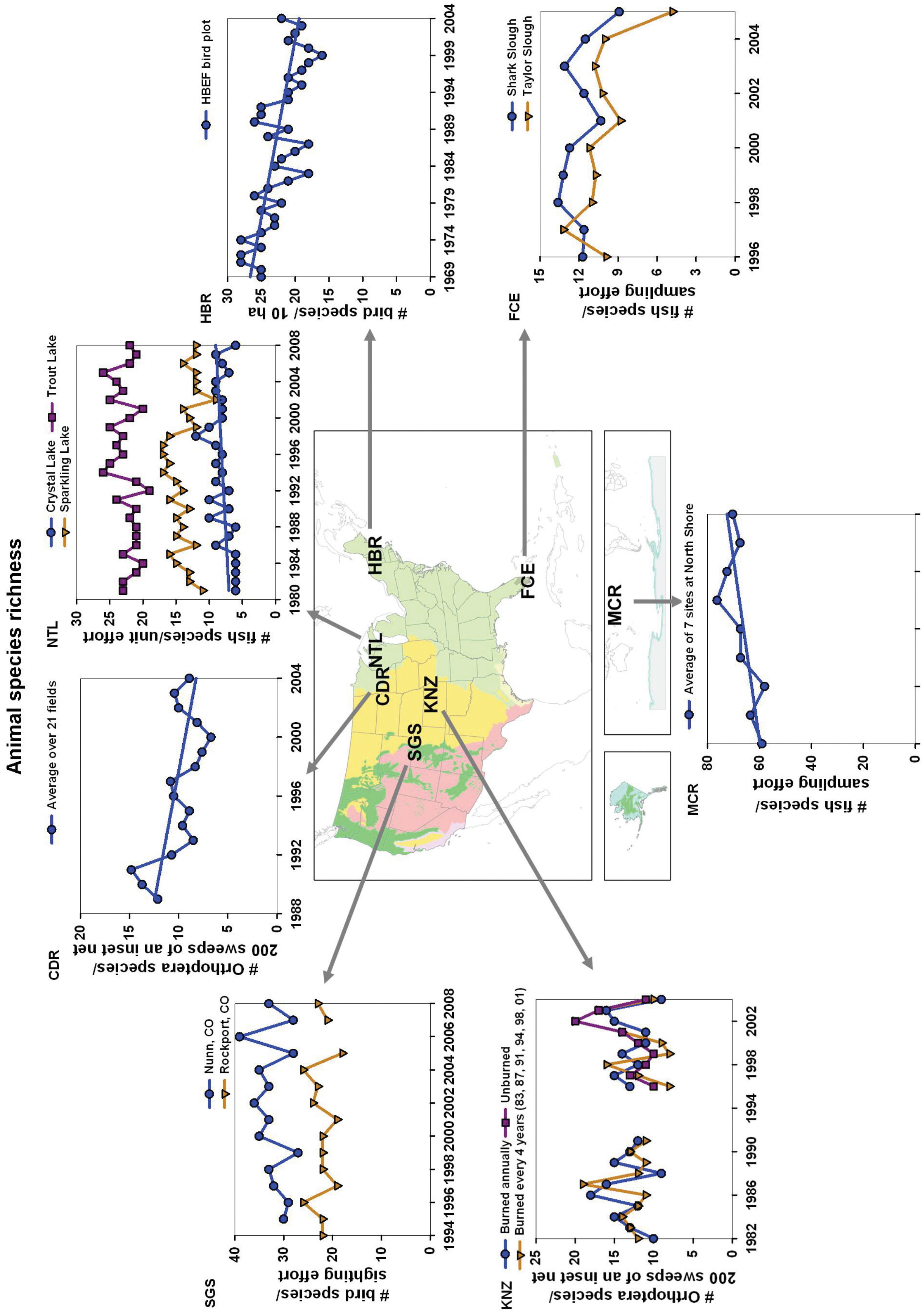

Figure 14-12. Animal species richness at seven sites (CDR, FCE, HBR, KNZ, MCR, NTL, and SGS). A simple linear regression line is displayed if the slope is statistically significant ($p < 0.05$) and the trend appears linear. The significant slopes are CDR (-0.28), HBR (-0.21), MCR (1.55), and NTL (0.07). 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.

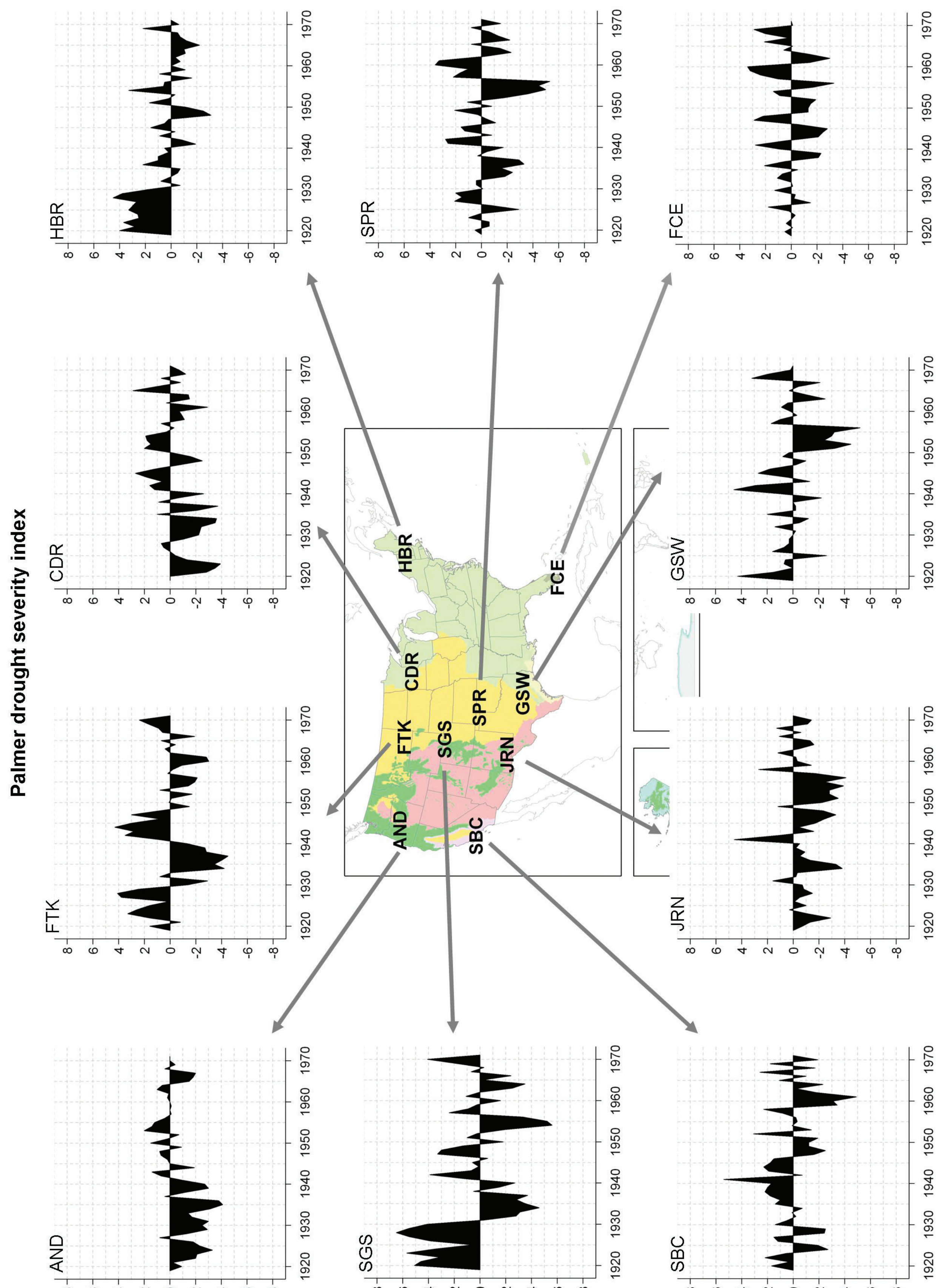

Figure 15-1. Fifty years of annual Palmer Drought Severity Indices for 10 key locations across the continental United States. Original data from http://www.ncdc.noaa.gov. Synthesized data from http://www.ecotrends.info.

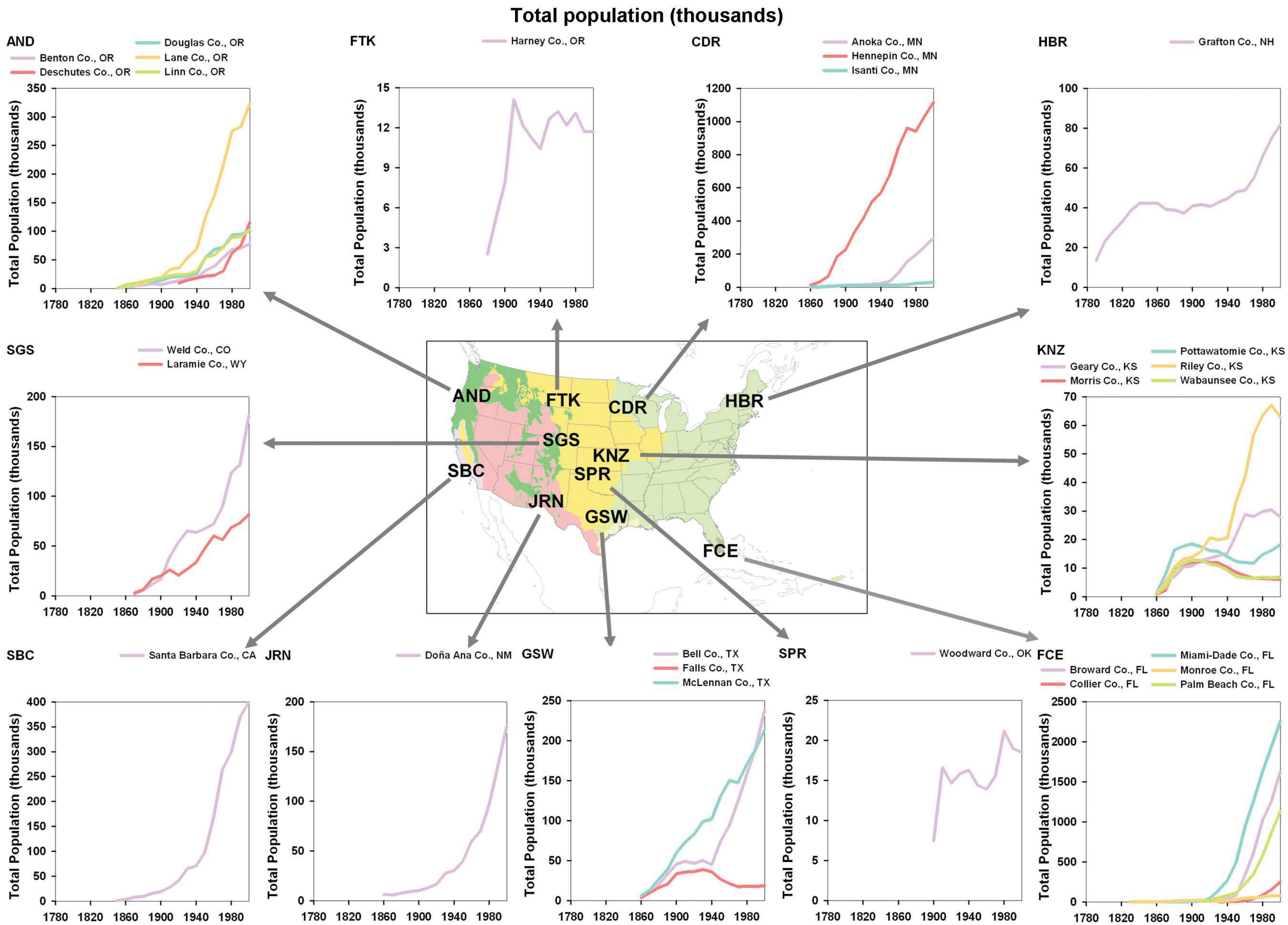

Figure 15-2. Long-term census data for 10 key locations across the continental United States. Original data from http://www.census.gov. Synthesized data from http://www.ecotrends.info.

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).

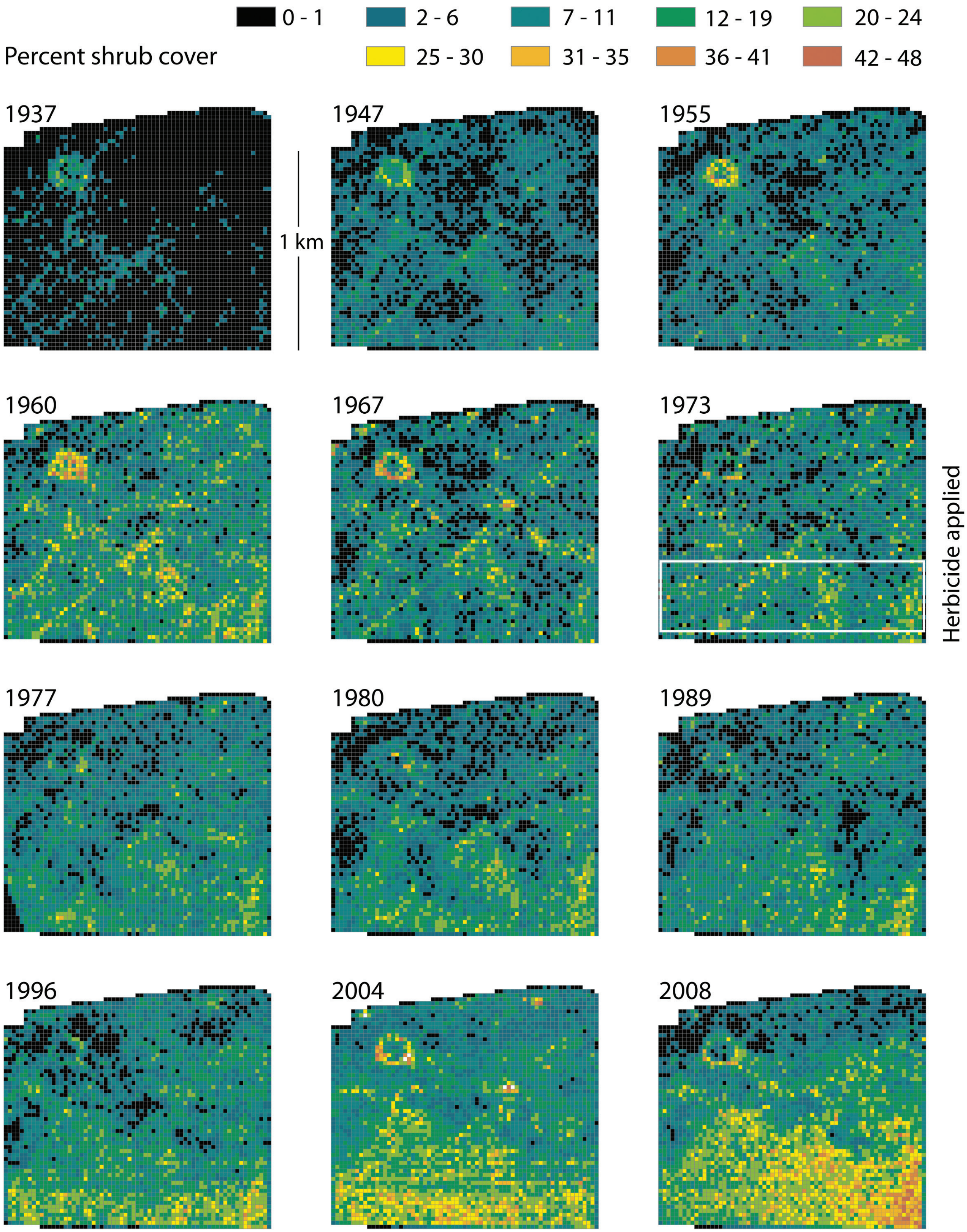

Figure 15-3. Repeat time series of aerial photographs over a 71-year period in southern New Mexico illustrating a variable increase in percentage of shrub cover through time as a result of extreme climatic events. Shrubs increased dramatically between 1937 and 1947 and again between 1996 and 2008. (D.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

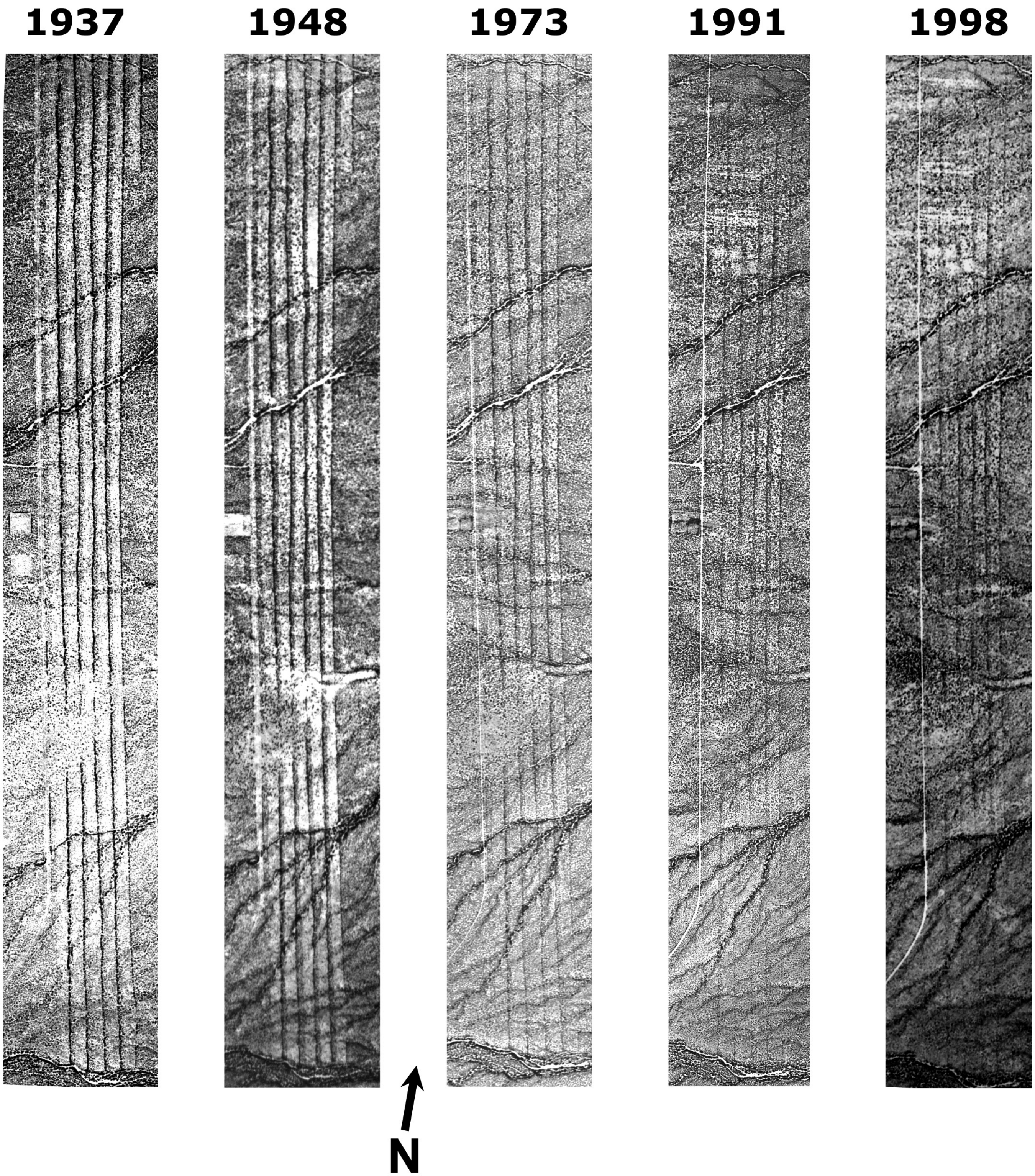

Figure 15-4. Temporal sequence over a 61-year period of alternating grubbed (shrubs physically removed at the ground-surface level; light-colored strips) and control areas (dark strips) in a predominantly creosotebush-dominated shrubland in southern New Mexico. Original grubbing was performed in 1936.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

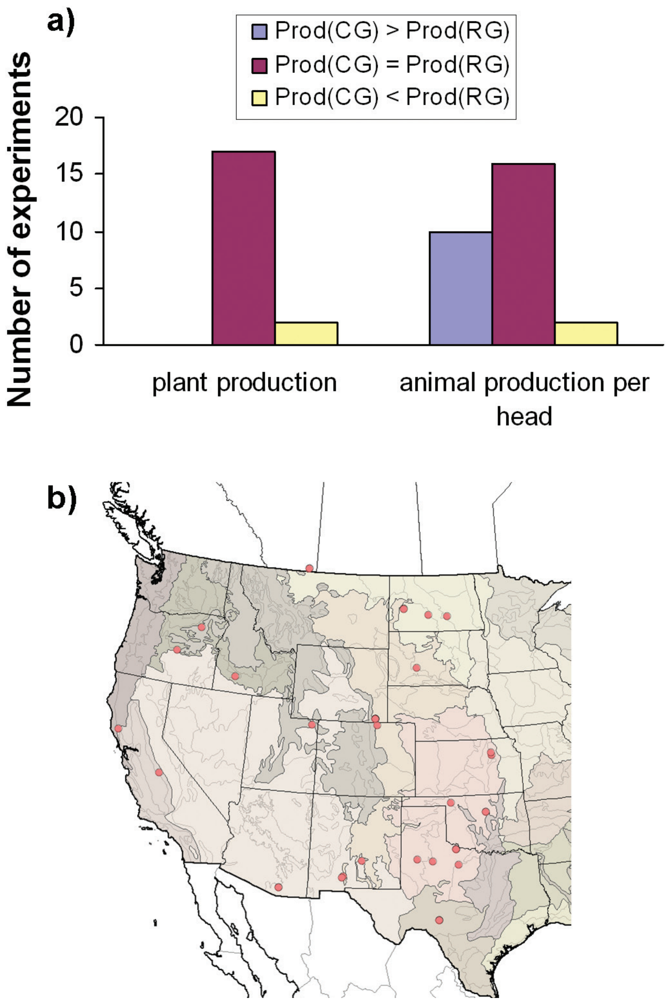

Figure 15-5. (a) Synthesis of research results from long-term studies of the response of plant and animal production to two common types of grazing systems: continuous grazing (CG) and rotational grazing (RG). When stocking rates were similar, 89 percent of the studies showed no difference in plant production 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.

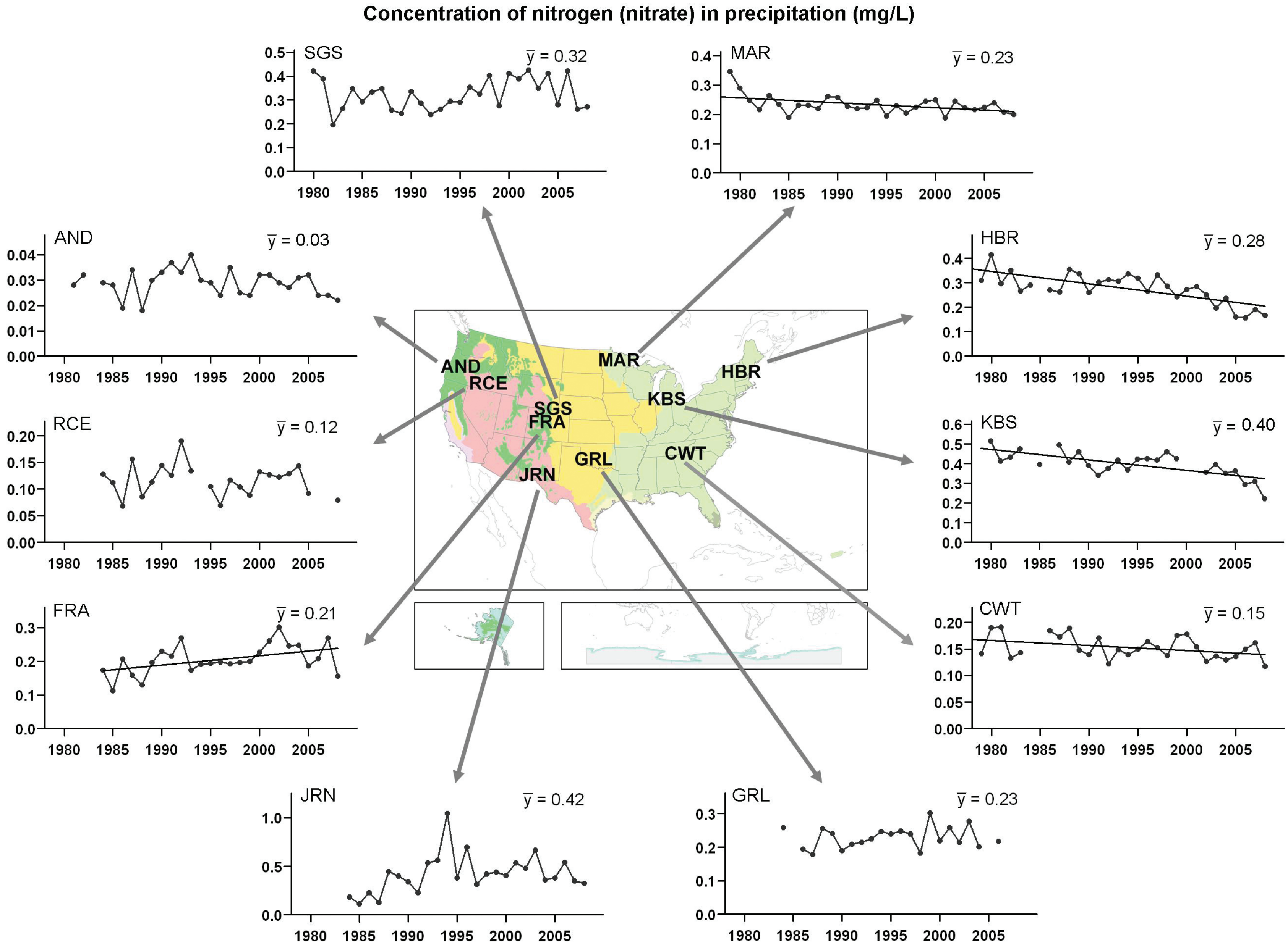

Figure 15-6. Nitrate concentrations recorded in precipitation (mg/L) over a 25-year period following Federal clean air policies enacted in the 1970s. Original data from http://nadp.sws.uiuc.edu/. Synthesized data from http://www.ecotrends.info.

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).

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.

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.

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

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

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

What Have We Learned Scientifically?

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

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

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

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

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

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

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

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

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

Conceptual Framework for Synthesis

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

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

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

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

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

Operational Framework for Synthesis

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

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

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

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

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

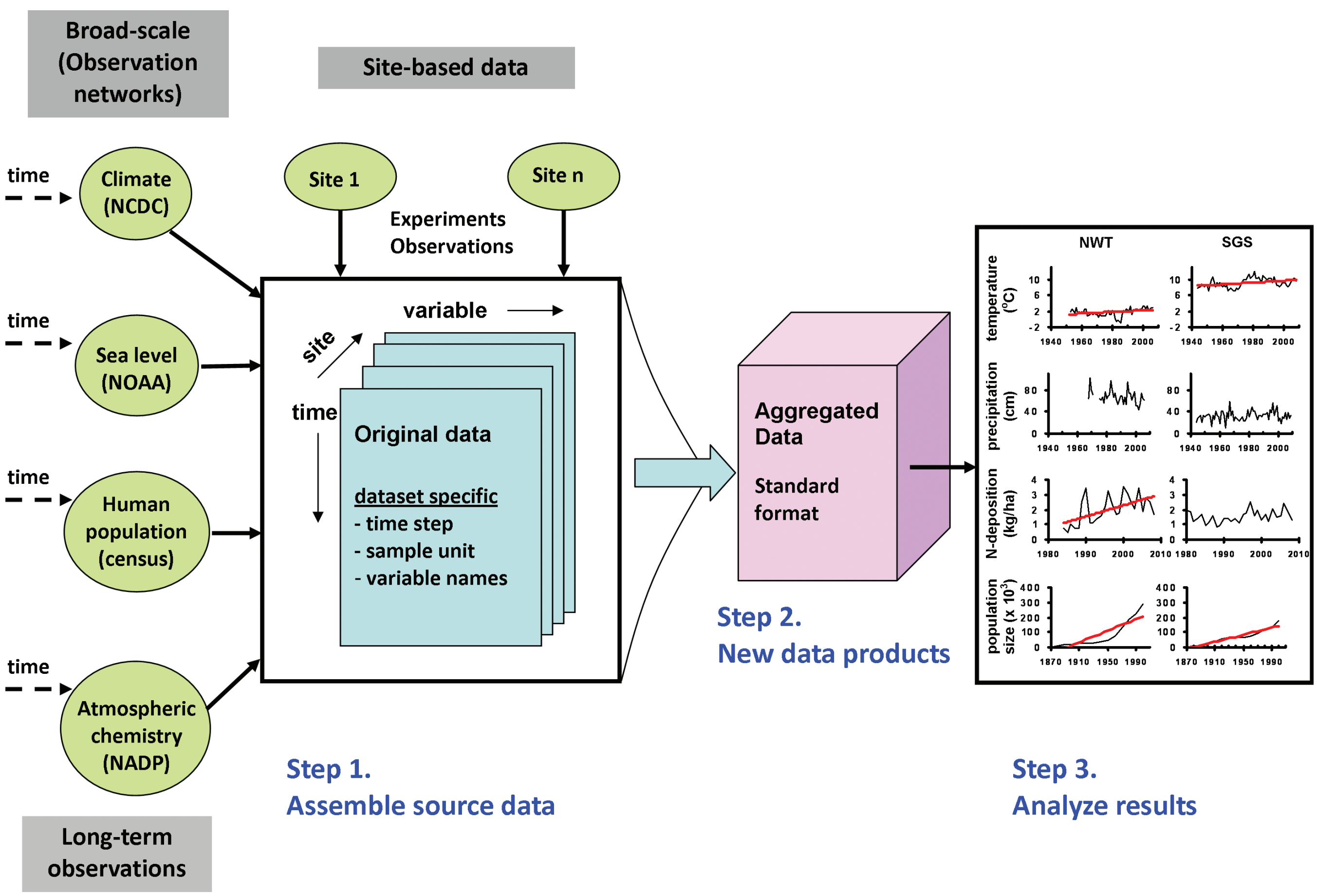

Figure 17-1. Operational framework for assembling different sources of data into a database of new products that allows and encourages cross-site comparisons and synthetic analyses. Redrawn from Peters (2010).

Recommendations: What Do We Still Need To Do?

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

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

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

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

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

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

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

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

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

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

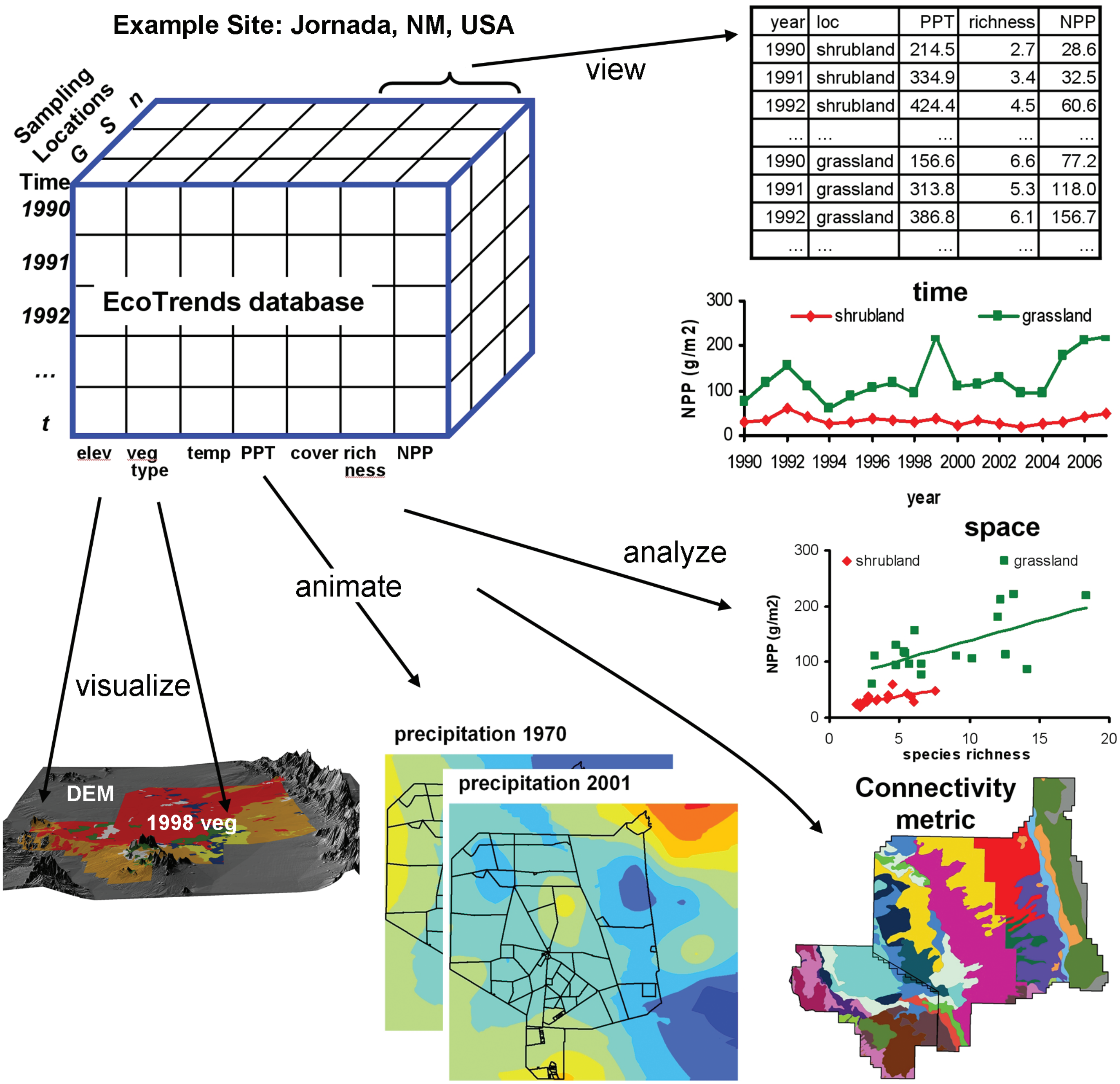

Figure 17-2. Web-based tools that allow visualization, animation, and analysis of derived data products are needed to fully utilize long-term data from many sites to address critical questions from a broad audience.

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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