Chapter 17
The Role of Experimental Forests and Ranges in the Development of Ecosystem Science and Biogeochemical Cycling Research

James M. Vose, Wayne T. Swank, Mary Beth Adams, Devendra Amatya, John Campbell, Sherri Johnson, Frederick J. Swanson, Randy Kolka, Ariel E. Lugo, Robert Musselman and Charles Rhoades

Abstract Forest Service watershed-based Experimental Forests and Ranges (EFRs) have significantly advanced scientific knowledge on ecosystem structure and function through long-term monitoring and experimental research on hydrologic and biogeochemical cycling processes. Research conducted in the 1940s and 1950s began as "classic" paired watershed studies. The emergence of the concept of ecosystem science in the 1950s and 1960s, the passage of the Clean Air Act and Clean Water Act in the 1970s, the nonpoint source pollution provision enacted in the Federal Water Pollution Control Act, and various other forces led to an increased interest in biogeochemical cycling processes. The ecosystem concept recognized

J. M. Vose (✉)
Department of Forestry and Environmental Resources, College of Natural Resources,
North Carolina State University, 5223 Jordan Hall, Box 8008, Raleigh, NC 27695, USA
Phone: 919-513-7367
e-mail: jvose@fs.fed.us

W. T. Swank
Southern Research Station (Emeritus), USDA Forest Service, Coweeta Hydrologic Laboratory,
3160 Coweeta Lab Road, Otto, NC 28763, USA

M. B. Adams
Northern Research Station, USDA Forest Service, Timber & Watershed Laboratory,
Route 219 North – Nursery Bottom, P.O. Box 404, Parsons, WV 26287, USA

D. Amatya
Southern Research Station, USDA Forest Service, Santee Experimental Forest,
3734 Highway 402, Cordesville, SC 29434, USA

J. Campbell
Northern Research Station, USDA Forest Service, 271 Mast Road, Durham, NH 03824, USA

S. Johnson
Pacific Northwest Research Station, USDA Forest Service, 3200 SW Jefferson Way,
Corvallis, OR 97331, USA

F. J. Swanson
Pacific Northwest Research Station (retired), USDA Forest Service,
H.J. Andrews Experimental Forest, P.O. Box 300, Blue River, OR 97413, USA

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that water, nutrient, and carbon cycles were tightly linked, and interdisciplinary approaches that examined the roles of soil, vegetation, and associated biota, as well as the atmospheric environment, were needed to understand these linkages. In addition to providing a basic understanding, several watershed-based EFRs have been at the core of the development and application of watershed ecosystem analysis to ecosystem management, and they continue to provide science to land managers and policy makers. The relevance and usefulness of watershed-based EFRs will only increase in the coming years. Stressors such as climate change and increased climate variability, invasive and noninvasive insects and diseases, and the pressures of population growth and land-use change increase the value of long-term records for detecting resultant changes in ecosystem structure and function.

Keywords Long-term data · Watersheds · Interdisciplinary · Nutrient cycling · Ecosystem management

17.1 Introduction

Forest Service watershed-based Experimental Forests and Ranges (EFRs) have been key for advancing knowledge on ecosystem structure and function through long-term monitoring and experimental research on hydrologic and biogeochemical cycling processes. Indeed, significant knowledge on the linkages among carbon, water, and nutrient cycling has been derived from EFRs whose original and primary mission was to understand the relationship between vegetation and hydrology. In most cases, the initial research conducted in the 1940s and 1950s began as “classic” paired watershed studies (Bosch and Hewlett 1982) where treatment watersheds (e.g., manipulating vegetation, fertilization, herbicide application) were compared to controls using streamflow measurements (amount and timing) as the primary response metric. Physically based water quality measurements (i.e., sediment, temperature, etc.) were often also co-measured to quantify the impacts of forest management activities and to support research efforts on the development of improved management systems that eventually led to the best management practices (BMPs).

R. Kolka
Northern Research Station, USDA Forest Service, 1831 Hwy 169 E,
Grand Rapids, MN 55744, USA

A. E. Lugo
International Institute of Tropical Forestry, USDA Forest Service, 1201 Calle Ceiba,
Jardín Botánica Sur, San Juan, PR 00926-1119, USA

R. Musselman · C. Rhoades
Rocky Mountain Research Station, USDA Forest Servcie, 240 West Prospect Road,
Fort Collins, CO 80526-2098, USA

EFRs have provided powerful empirical tools (i.e., regression models, numerical models, graphical analyses, etc.) that could be used to predict the impacts of forest vegetation changes on water yield and water quality in many areas of the USA. The value of these studies cannot be overstated; however, the watershed ecosystem was treated as a black box with little attention paid to the within watershed structural components and biological processes that regulate hydrologic and biological responses. Understanding hydrologic responses to forest management and natural disturbances remains highly relevant. Greater demand for drinking water and increased frequency of both chronic and acute disturbances continue to increase the value of investments in long-term hydrologic monitoring and watershed manipulation experiments. Many of these long-term watershed EFRs were, and continue to be, valued for more than understanding hydrologic responses.

17.2 The Evolution from Hydrology to Ecosystem Science

The emergence of the concept of ecosystem science in the 1950s and 1960s, the passage of the Clean Air Act and Clean Water Act in the 1970s, the nonpoint source pollution provision enacted in the Federal Water Pollution Control Act, and various other forces led to an increased interest in water quality and the biogeochemical cycling processes that determine how ecosystems cycle carbon and nutrients, and ultimately influence water quality. Many EFRs were uniquely positioned to be major players in ecosystem science and associated biogeochemical cycling research. Small watersheds provided convenient study units for defining ecosystems and testing ecosystem concepts developed by E.P Odum and others in the 1950s and 1960s (Odum 1959; Bormann and Likens 1967; Odum 1969). Furthermore, the strength of watershed-based EFRs came from the long-term hydrologic, climatic, and vegetation records already collected, as well as the capacity to conduct experimental treatments that allowed for testing hypotheses related to the regulatory influences of vegetation on biogeochemical cycling processes. Development of nutrient budgets and fluxes was an approach familiar to Forest Service researchers working at watershed-based EFRs who had been quantifying water fluxes using mass balance and classic paired watershed studies for decades. The transition to biogeochemical cycling required adding chemical analyses to the input and output variables and conducting within watershed process studies to determine linkages among carbon, water, and nutrient cycling processes. As of 2008, 15 EFRs (Table 17.1) are engaged in at least some aspect of both hydrology and biogeochemical cycling research, and their spatial distribution provides a wide coverage of climate, soils, and vegetation gradients (Fig. 17.1) in the continental USA and the islands of Hawaii and Puerto Rico (Adams et al. 2008). Some are relatively new EFRs (e.g., Baltimore, Hawaii), some began incorporating biogeochemical cycling components into their long-term research program within the past several years (e.g., Tenderfoot), while others have a history of using biogeochemical cycling approaches to address hypotheses related to ecosystem structure and function that extends back to the 1950s and 1970s (e.g., Hubbard Brook, Coweeta, Fernow, Marcell, H.J. Andrews, and Calhoun).

Table 17.1 Description of watershed EFRs with long-term monitoring of streamflow, precipitation chemistry, and stream chemistry. (Source: Information developed from a combination of EFR websites, Adams et al. 2008, and input from on-site EFR personnel)

Experimental forest	Location	Major vegetation	Streamflow	Precipitation chemistry	Stream chemistry
Baltimore	Baltimore, MD	Hardwood forest to urban	1999	1999	1999
Coweeta	Western North Carolina	Oak-hickory, cove, northern hardwoods	1934	1972	1972
Fernow	West Virginia	Mixed mesophytic hardwood	1951	1978	1971
Fraser	Colorado	Subalpine forest/alpine tundra	1941	1982	1982
Glacier lakes	Wyoming	Englemann spruce/subalpine fir	1989	1989	1989
Hawaii	Hawaii	Wet and dry tropical forest and grassland	In progress	In progress	In progress
H.J. Andrews	West Cascades, Oregon	Douglas fir/western hemlock	1949	1968	1968
Hubbard Brook	New Hampshire	Northern hardwoods/spruce–fir	1956	1963	1963
Luquillo	Puerto Rico	Evergreen broadleaf tropical forest	1945 (USGS) 1988 (USDA FS)	1988	1986
Marcell	Minnesota	Forested peatlands/upland hardwoods	1961	1978	1967
Sagehen	California	Grassland/shrub mixed conifer	1953 (USGS)	2001	1968 (USGS)
San Dimas	Southern California	Mixed chaparral	1939	1988	1982
Santee	Huber, South Carolina	Loblolly and longleaf pine/mixed pine-hardwood	1967	1976–1979, 2009	1976
Tenderfoot Creek	Central Montana	Subalpine fir	1992	n/a	1992–1993, 2001

USDA FS US Department of Agriculture Forest Service

Fig. 17.1 Location of EFRs currently measuring streamflow, atmospheric deposition, and stream chemistry in relation to other monitoring sites in the USA

The ecosystem concept recognized that water, nutrient, and carbon cycles were tightly linked, and interdisciplinary approaches that examined the roles of soil, vegetation, and associated biota, as well as the atmospheric environment, were needed to understand these linkages (Fig. 17.2). The complexity of the issue required non-traditional research approaches; some of the earliest and best examples of interdisciplinary research come from watershed EFRs. For example, starting in the mid-1950s and early 1960s, several EFRs initiated biogeochemical research, usually in collaboration with university partners and with external funding from the National Science Foundation (NSF) and other non-Forest Service-funding sources. The USDA Forest Service, NSF, and NSF International Biological Program (IBP) provided funding for some of the earliest EFR sites to initiate ecosystem studies. Examples include long-term soil nutrient studies at the Calhoun Experimental Forest initiated in the mid-1950s with a sample archive beginning in 1962, biogeochemical cycling research at Hubbard Brook (studies and long-term data collection began in 1963), and the Coweeta Hydrologic Laboratory (IBP-funded studies initiated in 1968; long-term data collection began in 1972). The primary focus of early research at the Calhoun, Hubbard Brook, and Coweeta was on understanding fundamental aspects of nutrient cycling patterns and process (Metz 1952, 1954; Bormann and Likens 1967; Johnson and Swank 1973; Wells and Jorgensen 1975), responses to natural and experimental disturbances, and responses to forest management, and forest growth and development (Wells and Jorgensen 1979; Swank et al. 1981; Swank 1988; Swank

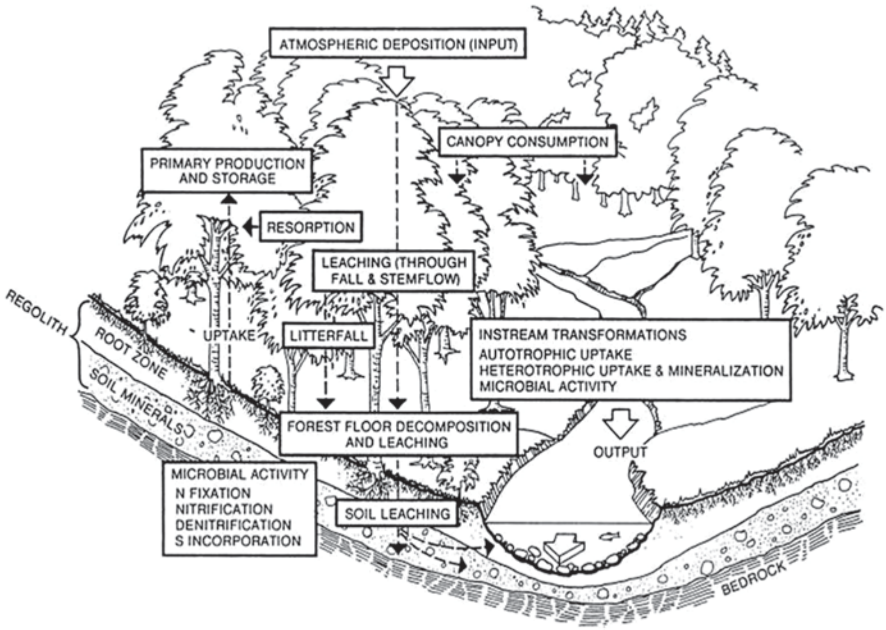

Fig. 17.2 Ecosystem components and processes regulating biogeochemical cycling in forest ecosystems

and Johnson 1994; Swank and Vose 1994; Markewitz et al. 1998). H.J. Andrews (streamflow measurements began in 1953) examined logging impacts on streamflow and water quality in the late 1950s and early 1960s, and expanded into ecosystem studies of biogeochemical cycling in forests and streams in small watershed during IBP in the late 1960s (Sollins et al. 1980; Sollins et al. 1981; Sollins and McCorison 1981;Triska et al. 1984). Research results from these early studies provide some of the best examples of the power of watershed analyses for understanding ecosystem structure and function (Franklin 1989). Building on this history, ecosystem research has continued and expanded at these sites to address contemporary issues using a combination of traditional measurement devices (e.g., weirs) and novel methods and approaches (e.g., stable isotopes, sensor networks, eddy covariance, etc.).

Other EFRs have incorporated biogeochemical cycling research into their research programs and long-term monitoring networks as well. For example, the Fernow Experimental Forest began measuring stream chemistry in 1971 and conducted watershed-scale fertilization studies beginning in 1989 to address issues related to acid deposition and nitrogen saturation (Adams et al. 2000; Edwards et al. 2002; Adams et al. 2006). The Marcell Experimental Forest began measuring stream chemistry in 1967 (Verry 1975) and mercury and organic carbon in the 1990s to determine the influence of forest management and peatlands on water quality and biogeochemical cycles (Kolka et al. 1999). Similarly, precipitation and stream water chemistry measurements at the Santee Experimental Forest (SEF) were initiated in early 1976. As a result, the impacts of prescribed burning on streamflow and water chemistry of the first-order coastal forested watersheds and chemical composition of precipitation at the SEF were examined during the early 1980s (Richter et al. 1982, 1983). Watershed research began in 1988 at the Luquillo Experimental Forest (Scatena 1989), 1 year before Hurricane Hugo passed over the Bisley Experimental Watersheds. This event led to detailed studies of how tropical forests respond to windstorms, an unprecedented record of biogeochemical, structural, compositional, and functional information for tropical forests (Scatena and Lugo 1995; Scatena et al. 1996; Heartsill-Scalley et al. 2007; Heartsill-Scalley et al. 2010; Fig. 8 in Lugo and Heartsill-Scalley, this volume) that is still continuing.

Forest Service EFRs also contribute to a worldwide network of long-term experimental watersheds focused on biogeochemical cycling throughout North America and Europe. Many of these sites were established to examine the impacts of acid deposition on surface water chemistry. In North America, examples include the Walker Branch Watershed in Oak Ridge, TN (established in 1967 by the US Atomic Energy Commission), the Panola Mountain Research Watershed in Georgia (established in1984 by the U.S. Geologic Survey), and The Turkey Lakes Watershed in Canada (established in 1980 by Environment Canada). In Europe, examples include the Plynlimon Watershed in Wales (established in 1968) and the Lake Gardsjon Watershed in Sweden (established in 1978).

Further details of the programmatic research history are available for Coweeta (Douglass and Hoover 1988; Swank et al. 2002), H.J. Andrews (Geier 2007), Calhoun (Metz 1958; Richter and Markewitz 2001), GLEES (Musselman 1994), Hubbard Brook (Likens and Bormann 1995; Groffman et al. 2004); Fernow (Adams et al. in preparation), Fraser (Stottlemyer and Troendle 1987), Marcell (Kolka et al. 2011; Sebestyen and Kolka submitted), and the SEF (Amatya and Trettin 2007a).

17.3 The Importance of Partnerships

A common theme among EFRs actively involved in ecosystem and biogeochemical cycling research is the importance of collaborative partnerships with universities, national programs and other federal agencies, private foundations, and other external funding sources. Several factors contribute to this commonality. Ecosystem science is complex and requires interdisciplinary approaches to understand the interactions among structural and functional components of carbon, nutrient, and water cycling processes. Although many Forest Service scientists have played major roles in ecosystem-based research at EFRs, few EFRs have had the full range of scientific expertise required to address complex and comprehensive ecosystem studies. Hence, large teams of specialists (e.g., hydrologists, soil scientists, plant ecologists, etc.) are often involved to cover the topical diversity. As such, strong collaborative research with universities, other federal and state agencies, and other institutions has developed at many watershed EFR sites (Table 17.2).

The benefits of these partnerships go beyond the value of the science. Forest Service watershed EFRs have played a major role in educating current and future generations of ecosystem and hydrologic scientists, both nationally and internationally.

Table 17.2 Collaborators, participation in national and international Networks, and funding provided from non-USDA Forest Service sources to support overall research at the EFR sites. (Source: Information developed from a combination of EFR websites, Adams et al. 2008, and input from on-site EFR personnel)

Experimental forest	Primary collaborators	National and international networks	Non-USDA FS funding sources
Baltimore	Johns Hopkins, University of North Carolina, Vermont University, University of Maryland, Columbia, Towson University	USGS, NADP, LTER	NSF
Calhoun	Duke University, North Carolina State University, University of Georgia	CZO	NSF, USDA-NRI, Andrew Mellon
Coweeta	University of Georgia, Virginia Tech, Duke, University of North Carolina-Chapel Hill, University of Minnesota, University of Wisconsin, Yale University, N. Carolina State University	NADP, NDDN, CASTnet, LTER, MAB Biosphere Reserves, Ameriflux	NSF, US-EPA, DOD, USDA-NRI
Fernow	West Virginia University, Pennsylvania State University, Virginia Tech.	NADP, CASTNet	US-EPA, NSF, USDA-NRI
Fraser	Colorado State University, University of Colorado,	USGS	US-EPA, USGS, NASA, NOAA
Glacier lakes	Colorado State University, University of Wyoming, Wake Forest University	NADP, CASTNet, Ameriflux, SNOTEL	US-EPA
Hawaii	University of Hawaii		
H.J. Andrews	Oregon State University, NASA	NADP, USGS, HBN, MDN, LTER	NSF
Hubbard Brook	Brown University, Dartmouth, Yale, Cornell, Syracuse, State University of New York, UC-Berkeley, University of New Hampshire, Wellesley College, Cary Institute of Ecosystem Studies, US Geological Survey	NADP, SCAN, MDN, CASTNet, LTER	NSF, DOE, USDA, A.W. Mellon Foundation, EPA, NRCS

Table 17.2 (continued)

Experimental forest	Primary collaborators	National and international networks	Non-USDA FS funding sources
Luquillo	University of Puerto Rico, U. New Mexico, UC-Berkeley, U. Pennsylvania, University of New Hampshire, Utah State, U. Connecticut, State University of New York-Syracuse, University of Georgia	NADP, USGS, LTER, CZO, MAB Biosphere Reserves, Smithsonian Biodiversity Plots	NSF
Marcell	University of Minnesota, University of Toronto, University of Wisconsin, Michigan Tech, Michigan State, University of Nebraska, North Carolina State, Gustavus Adolphus College	NADP, MDN	US-EPA, NASA, DOE, NSF, NSERC
Sagehen	UC-Berkeley	NADP	
San Dimas	UC-Riverside, University of Georgia, University of Iowa, Cal Poly-Pomona, Cal State-Long Beach,	NADP	
Santee	College of Charleston, Clemson, University of South Carolina, Virginia Tech, University of New Hampshire	USGS	US-EPA, South Carolina EPD
Tenderfoot	Montana State University, University of Montana	USGS, SNOTEL, AmeriFlux	

CZO Critical Zone Observatory, *DOD* Department of Defense, *DOE* Department of Energy, *EPD* Environmental Protection Division, *MAB* Man and the Biosphere Programme, *MDN* Mercury Deposition Network, *NADP* National Atmospheric Deposition Program, *NASA* National Aeronautics and Space Administration, *NDDN* National Dry Deposition Network, *NRCS* Natural Resources Conservation Service, *USDA* United States Department of Agriculture-National Research Initiative, *USDA FS* US Department of Agriculture Forest Service, *US-EPA* United States Environmental Protection Agency

For example, nearly 1,000 students have received graduate degrees from work conducted at Coweeta (~270), Hubbard Brook (~190), Fernow (~50), Fraser (~50), H.J. Andrews (~240), Marcell (~30), Luquillo (~100), and the Calhoun and Santee (~20). National monitoring programs such as the National Atmospheric Deposition Program (NADP), the Mercury Deposition Network (MDN), National Dry Deposition Network (NDDN, CASTnet), and other federal agencies such as the US Geological Survey (USGS) have collaborated or provided data on precipitation chemistry, water quality, and streamflow at several of the sites (Table 17.2). For example, USGS and National Park researcher Bob Stottlemyer added complementary biogeochemical research to ongoing Forest Service hydrologic studies at the Fraser Experimental Forest and supported this partnership for two decades.

Success in leveraging funding in addition to that provided by the USDA Forest Service has also been an important key to the success of many of these programs. Most notably, the NSF recognized that long-term approaches were required for understanding ecosystem processes, and the Coweeta Hydrologic Laboratory and the H.J. Andrews Experimental Forests were among the original eight NSF Long-Term Ecological Research (LTER) Sites established in 1980; they were followed by Bonanza Creek in 1987, Hubbard Brook in 1988, Luquillo in 1988, and Baltimore in 1997. Current and future relevance of the long-term data records is evidenced by involvement of several EFRs in the formation of two emerging national networks: (1) National Ecological Observation Network (NEON) and (2) Urban Long-Term Research Area (ULTRA). The LTER program is not the only additional funding source that helps sustain EFR research; however, most of these other funding sources are typically shorter term. Other sources of funding include the Environmental Protection Agency, the NSF, private foundations, various state agencies, USDA National Research Initiative, NASA, Department of Defense, Electric Power Research Institute, National Council for Air and Stream Improvement, Department of Energy, and various others. Another recent example of a partnership involving the SEF is the Turkey Creek Watershed initiative, a multiagency eco-hydrological research collaboration to address the critical issues of sustainable water management for the low-gradient coastal landscape (Amatya and Trettin 2007b).

17.4 Applying Ecosystem Science to Forest Management

Long-term partnerships with USDA Forest Service managers, resource specialists, and decision makers ensure that research conducted at the EFRs is responsive to the resource management challenges on National Forests. EFR scientists and staff provide a ready outlet for science delivery to land managers, and most EFRs contribute frequently to technical tours and educational field trips for the public. Demonstration areas and self-guided tours are also active outlets for sharing research findings.

Several watershed-based EFRs have been at the core of the development and application of watershed ecosystem analysis to ecosystem management (Kessler et al. 1992). For example, researchers at Hubbard Brook (Likens 1989; Hornbeck and Swank 1992), Coweeta (Swank and Johnson 1994; Meyer and Swank

1996), H.J. Andrews (Franklin et al. 1981), and Luquillo (Lugo and Scatena 1995; Lugo et al. 1999) were leaders in providing the conceptual basis for ecosystem management. The combination of an ecosystem-based research approach with watershed scale experimental treatments that included forest management practices (e.g., logging, road construction, etc.) provided data and real-world examples to test the often "fuzzy" concepts of ecosystem management (Christensen et al. 1996). For example, research at Hubbard Brook and Coweeta provided watershed ecosystem analysis methods to evaluate effects of harvesting practices, acidic deposition, and past land use (Hornbeck and Swank 1992). Studies at Marcell and Coweeta have been critical to developing BMPs for forestry in the midwest (Verry 1976; Verry et al. 1983) and southeast regions of the USA (Phillips et al. 2000; Riedel et al. 2007). Results from research at EFRs have had a significant impact on many forest management and environmental policy issues in the USA. For example, watershed research and studies of old-growth forest ecosystems at H.J. Andrews contributed substantially to the development and early implementation of the Northwest Forest Plan (Cissel et al. 1994).

A few EFRs expanded their research beyond the EFR boundary to demonstrate and test the application of ecosystem management concepts in partnership with natural resource managers. For example, Coweeta initiated the Wine Spring Creek Ecosystem Management Project (WSC) with the objective of using ecosystem-based concepts, principles, and technology to achieve desired resource conditions (Swank and Van Lear 1992). Participants in the project included an interdisciplinary team of over 55 scientists and managers in five research units in the Southern Research Station; the National Forest Systems and seven universities; state agencies; environmental conservation groups; and the public. A consensus-building process comprising of workshops attended by all stakeholders was conducted over an 18-month period. From this consensus-fielding process, 35 desired future resource conditions were identified for the project area. Management prescriptions were applied to achieve desired future conditions, and then monitored for response, followed by application of adaptive management if needed. Findings from individual studies proved useful in making management decisions and an EMERGY-based environmental systems assessment to integrate and quantify the balance of ecological, economic, and social demands placed on land resources (Tilley and Swank 2003). Watershed ecosystem principles were at the core of the research–management interface since water transports materials within and from the forested landscape, and water cycles are tightly linked with carbon and nutrient cycling processes. Other examples include research synthesis products that have been developed based on work in northeastern (Hubbard Brook) and midwestern (Marcell) experimental forests to inform forest managers of ecosystem impacts of management (Verry et al. 2000). More recent work has integrated research results from Marcell to help understand the effects of land use and fragmentation on stream systems and biologic communities in midwestern landscapes (Verry 2004). At the Luquillo Experimental Forest, watershed research led to a new design for water extraction, which prevented the damming of the river and allows for water extraction without affecting the two-way migration of critical stream fauna (March et al. 2003). Like many EFRs, the ecosystem studies at the Fraser Experimental Forest were designed to quantify the effects of vegetation manipulation associated with forest management activities on soil nutrient cycling and stream water nutrient export (Reuss et al. 1997; Stottlemyer and Troendle 1999). Extensive overstory mortality caused by mountain pine beetle outbreak throughout much of the interior west has taken Fraser's watershed studies in a new direction. Historic studies now will allow comparison of the response of paired basins with varying management history and stand structure (e.g., regenerating vs. old-growth forest) to a natural forest disturbance. For example, in the years immediately following beetle infestation resulting in the loss of 40% of total overstory basal area, nitrate concentrations increased in old-growth basins compared to the pre-infestation stream water record (Rhoades et al. 2008).

17.5 Challenges and Opportunities

EFRs have been critical for addressing fundamental questions related to ecosystem structure and function and for applying ecosystem concepts to the management of forest and range ecosystems. This national network of long-term climate, hydrologic, biogeochemical, vegetation, and land-use records that address fundamental resource management and ecosystem concepts provides a unique niche that facilitates collaboration with academic institutions and other federal and state agencies. Despite their important historic contributions and their current role in development of continental-scale ecological networks aimed at addressing climate and land-use change, EFRs face significant challenges maintaining long-term data collection and research facilities management. These challenges are consistent with those discussed in recent reviews by Ice and Stednick (2004) and Stednick et al. (2004) who compiled lessons learned from watershed research throughout the country, with most information derived from Forest Service EFRs. Most EFRs struggle with the substantial (and growing) fixed costs associated with the collection, analyses, and data management (QA/QC, storage, and access systems) required for monitoring precipitation volume and chemistry, streamflow volume and chemistry, ground water levels, and all other associated measurements (e.g., climate, soils, vegetation, etc.) required to understand ecosystem structure and function.

The value of long-term ecosystem measurements is substantial and the return on investment will continue to grow. As an example, stream NO_3 concentration has been measured for more than 30 years after clearcutting a hardwood forest at Coweeta (Fig. 17.3). The three time trends noted on the graph represent patterns observed over a ~5-year period. If the monitoring had been stopped with the assumption that the response trajectory observed over the previous 5-year period was going to continue into the future, the assumption (and associated interpretations of physical and biological factors regulating the response) would have been wrong in every case. While this example is based on measurements from a manipulated watershed, long-term baseline measurements from reference watersheds are also critical for detecting responses to forcings such as climate change, vegetation development, atmospheric deposition, insects and disease, and whatever else the future holds. These data also provide important reference data for evaluating restoration

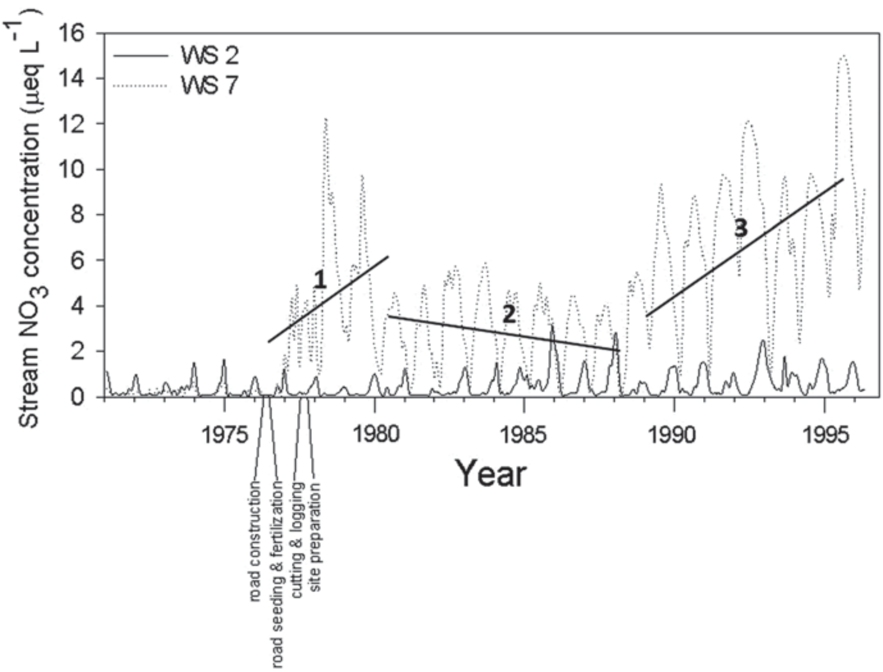

Fig. 17.3 Nitrate nitrogen concentration in stream water from a reference (*solid line, WS2*) and clearcut watershed (*dashed line, WS7*) at Coweeta. Three distinct tends in stream NO_3 were observed: *1*=an increase in response to cutting and road bank fertilization, *2*=a decrease in response to vegetation regrowth and N uptake, and *3*=an increase in response to unknown factors (e.g., black locust mortality, enhanced decomposition) that are currently being examined.

success on degraded watersheds. Second, the relevancy of EFRs will require looking beyond the EFR boundary. For example, many contemporary issues are global (i.e., climate change, invasive) or regional (e.g., land-use change, drought) in scale, yet EFRs have been traditionally inward-looking with the majority of research activities focused on the site. To continue to be relevant, EFRs will be challenged to scale site-based research to larger spatial scales and expand experimental and observational approaches beyond EFR boundaries, while at the same time, maintaining the in-depth, long-term research within the EFR. Expanding beyond the watershed boundary will require that the human dimension of ecosystem science be directly addressed—humans are both a part of ecosystems and depend upon them for the services they provide. Despite the importance of the human dimension, few EFRs have the scientific expertise or experience in integrating social and ecological sciences. Finally, it has become increasingly difficult to conduct manipulative experiments at EFRs due to the challenges associated with meeting National Environmental Policy Act (NEPA) requirements. Novel experiments are at the very core of testing complex ecosystem hypotheses, yet the "experimental" component of the EFR has been considerably restricted in recent years. Indeed, historical whole watershed manipulations such as preventing regrowth after cutting, species conversions, grazing, herbicides, acidification, long-term prescribed burning have yielded (and continue to yield) considerable insight into ecosystem processes. The ability of EFRs to efficiently conduct manipulations required to address contemporary issues will be a critical determinant of their value in the twenty-first century.

Despite these challenges, the relevance and usefulness of watershed-based EFRs will increase in the coming years. Stressors such as climate change and increased climate variability, invasive and noninvasive insects and diseases, and the pressures of population growth, and land-use change increase the value of long-term records for detecting resultant changes in ecosystem structure and function. Much of these long-term records are high quality, and improvements in networking and accessibility via electronic data bases such as HydroDB and ClimDB (http://www.fsl.orst.edu/climdb/harvest.htm) make them available to the greater scientific community.

17.6 Conclusions

Forest Service EFRs have played an important role in the development of ecosystem science. Early approaches focused heavily on biogeochemical and hydrologic cycling processes as key metrics for testing ecosystem hypotheses, but have expanded to include understanding linkages between climate change and carbon cycling as well. EFRs will continue to play an important role in ecosystem science and will be critical for measuring and predicting impacts of an altered atmospheric environment and other forest health threats in the future. Long-term data and experiments are available from watershed-based EFRs spanning across wide geographic, vegetation, and climate gradients to test and develop models required to predict ecosystem responses to contemporary and future forcing variables such as climate change, invasive species, and other pressures associated with increased human population growth and growing demand for ecosystem services.

References

Adams MB, Burger JA, Jenkins AB, Zelazny L (2000) Impact of harvesting and atmospheric pollution and nutrient depletion of eastern U.S. hardwood forests. For Ecol Manage 138(1):301–319

Adams MB, DeWalle DR, Hom JL (eds) (2006) The Fernow watershed acidification study. Springer-Verlag, New York, 279 p

Adams MB, Loughry L, Plaugher L (comp.) (2008) Experimental Forests and Ranges of the USDA Forest Service. General Technical Report NE-321 Revised, U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, PA, 178 p, [CD ROM]

Amatya DM, Trettin CC (2007a) Development of watershed hydrologic research at Santee Experimental Forest, Coastal South Carolina. In: Furniss M, Clifton C, Ronenberg K (eds) Advancing the fundamental sciences: proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, October 18–22, 2004, PNW-GTR 689, US Department of Agriculture, Forest Service Pacific Northwest Station, Portland, OR

Amatya DM, Trettin CC (2007b) An eco-hydrological project on Turkey Creek Watershed, South Carolina, U.S.A. In: Meire P et al (eds) Integrated water management: practical experiences

and case studies, NATO science series IV: earth and environmental sciences. Springer, Netherlands, pp 115–126
Bormann FH, Likens GE (1967) Nutrient cycling. Science 155:424–429
Bosch JM, Hewlett JD (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J Hydro 55:3–23
Christensen NL, Bartuska AM, Brown JH, Carpenter S, D'Antonio C, Francis R, Franklin JF, MacMahon JA, Noss RF, Parsons DJ, Peterson CH, Turner MG, Woodmansee RG (1996) The report of the ecological society of America committee on the scientific basis for ecosystem management. Ecol Appl 6:665–691
Cissel JH, Swanson FJ, McKee WA, Burditt AL (1994) Using the past to plan the future in the Pacific Northwest. J For 92(8):30–31, 46
Douglass JE, Hoover MD (1988) History of Coweeta. In: Swank WT, Crossley DA Jr (eds) Forest hydrology and ecology at Coweeta. Ecological studies, vol 66. Springer-Verlag, New York, pp 17–31
Edwards PJ, Kochenderfer JN, Coble DW, Adams MB (2002) Soil leachate responses during 10 years of induced whole-watershed acidification. Water Air Soil Pollut 140:99–118
Franklin JF (1989) Importance and justification of long-term studies in ecology. In: Likens GE (ed) Long-term studies in ecology: approaches and alternatives. Springer-Verlag, New York, pp 3–19
Franklin JF, Cromack K Jr, Denison W, McKee A, Maser C, Sedell J, Swanson F, Juday G (1981) General Technical Report PNW-GTR-118, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 48 p
Geier MG (2007) Necessary work: discovering old forests new outlooks, and community on the HJ Andrews Experimental Forest, 1948–2000. USDA, Forest Service, Pacific Northwest Research Station. General Technical Report PNW-GTR687, 357 p
Groffman PM, Driscoll CT, Likens GE, Fahey TJ, Holmes RT, Eagar C, Aber JD (2004) Nor gloom of night: a new conceptual model for the Hubbard Brook ecosystem study. BioScience 54:139–148
Heartsill-Scalley T, Scatena FN, Estrada C, McDowell WH, Lugo AE (2007) Disturbance and long-term patterns of rainfall and throughfall nutrient fluxes in a subtropical wet forest in Puerto Rico. Journal of Hydrology 333:472–485
Heartsill-Scalley T, Scatena FN, Lugo AE, Moya S, Estrada-Ruiz C (2010) Changes in structure, composition and nutrients during 15 year of hurricane-induced succession in a subtropical wet forest in Puerto Rico. Biotropica 42:455–463
Hornbeck JW, Swank WT (1992) Watershed ecosystem analysis as a basis for multiple-use management of eastern forests. Ecol Appl 2(3):238–247
Ice G, Stednick JD (eds) (2004) A century of forest and wildland lessons. Society of American Foresters, Bethesda, 287 p
Johnson PL, Swank WT (1973) Studies on cation budgets in the southern Appalachians on four experimental watersheds with contrasting vegetation. Ecology 54:70–80
Kessler WB, Salwasser H, Cartwright CW Jr, Caplan JA (1992) New perspectives for sustainable natural resources management. Ecol Appl 6:738–740
Kolka RK, Grigal DF, Verry ES, Nater EA (1999) Mercury and organic carbon relationships in streams draining forested upland/peatland watersheds. J Environ Qual 28:766–775
Kolka RK, Sebestyen SD, Verry ES, Brooks KN (eds) (2011) Peatland biogeochemistry and watershed hydrology at the Marcell experimental forest. CRC Press, Boca Raton
Likens GE (ed) (1989) Long-term studies in ecology: approaches and alternatives. Sringer-Verlag, New York
Likens GE, Bormann FH (1995) Biogeochemistry of a forested ecosystem, 2nd edn. Springer-Verlag New York Inc., New York, 159 p
Lugo AE, Scatena FN (1995) Ecosystem-level properties of the Luquillo experimental forest with emphasis on the tabonuco forest. In: Lugo AE, Lowe C (eds) Tropical forests: management and ecology. Springer, New York, pp 59–108
Lugo AE, Baron JS, Frost TP, Cundy TW, Dittberner P (1999) Ecosystem processes and functioning. In: Szaro RC, Johnson NC, Sexton WT, Malk AJ (eds) Ecological stewardship: a common reference for ecosystem management. Elsevier Science, Oxford, pp 219–254

March JG, Benstead JP, Pringle CM, Scatena FN (2003) Damming tropical island streams: problems, solutions, and alternatives. Bio Sci 53:1069–1078

Markewitz D, Richter DD, Allen HL, Urrego JB (1998) Three decades of observed soil acidification at the Calhoun experimental forest: has acid rain made a difference? Soil Sci Soc Am J 62:1428–1439

Metz LJ (1952) Weight and nitrogen and calcium content of the annual litter fall of forests in the South Carolina Piedmont. Soil Sci Soc Am Proc 16:38–41

Metz LJ (1954) Forest floor in the Piedmont region of South Carolina. Soil Sci Soc Am Proc 18:335–338

Metz LJ (1958) The Calhoun experimental forest. Southeastern Forest Experiment Station, Asheville, p 24

Meyer JL, Swank WT (1996) Ecosystem management challenges ecologists. Ecol Appl 6(3):738–740

Musselman RC (technical editor) (1994) The glacier lakes ecosystem experiments site. General Technical Report RM-249. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, p 96. http://www.fs.fed.us/rm/pubs_rm/rm_gtr249.html

Odum EP (1959) Fundamentals of ecology, 2nd edn. Saunders, Philadelphia

Odum EP (1969) The strategy of ecosystem development. Science 164:262–270

Philips MJ, Swift LW Jr, Blinn CR (2000) Best management practices for riparian areas. In: Verry ES, Hornbeck JW, Dolloff CA (eds) Riparian management of forests of continental eastern. U.S. Lewis Publishers, Boca Raton, pp 272–285

Reuss JO, Stottlemyer R, Troendle CA (1997) Effect of clearcutting on nutrient fluxes in a subalpine forest at Fraser, Colorado. Hydrol Earth Syst Sci 1:333–344

Rhoades C, Elder K, Hubbard R, Dixon M (2008) Streamwater chemistry and nutrient export during five years of bark beetle infestation of subalpine watersheds at the Fraser experimental forest, Eos Trans. AGU, 89(53), Fall Meeting Suppl, AbstractH13C-0929

Richter DD, Ralston CW, Harms WR (1982) Prescribed fire: effects on water quality and forest nutrient cycling. Science 215:661–663

Richter DD, Ralston CW, Harms WR (1983) Chemical composition and spatial variation of bulk precipitation at a coastal plain watershed in South Carolina. Water Resour Res 19(1):134–140

Richter DD, Markewitz D (2001) Understanding soil change: sustainability of soils over millennia, centuries, and decades. Cambridge University Press, UK

Riedel MS, Swift LW Jr, Vose JM, Clinton BD (2007) Forest road erosion research at the Coweeta hydrologic laboratory. In: Furniss M, Clifton C, Ronnenberg K (eds) Advancing the fundamental sciences, pp 197–205. Proceedings of the Forest Service National Earth Science Conference, 18–22 October 2004, San Diego, CA PNW-GTR-689, USDA Forest Service, Pacific Northwest Research Station, Portland, OR

Scatena FN (1989) An introduction to the physiography and history of the Bisley experimental watersheds in the Luquillo Mountains of Puerto Rico. General Technical Report SO-72, USDA Forest service, Southern Forest Experiment Station, New Orleans

Scatena FN, Lugo AE (1995) Geomorphology, disturbance, and the soil and vegetation of two subtropical wet steepland watersheds of Puerto Rico. Geomorphology 13:199–213

Scatena FN, Moya S, Estrada C, Chinea JD (1996) The first five years in the reorganization of aboveground biomass and nutrient use following Hurricane Hugo in the Bisley Experimental Watersheds, Luquillo Experimental Forest, Puerto Rico. Biotropica 28:424–440

Sebestyen S, Kolka R (submitted) Experimental forest and range synthesis: Marcell experimental forest. General Technical Report WO-XX, USDA Forest Service, Washington Office, Washington DC

Sollins P, McCorison FM (1981) Nitrogen and carbon solution chemistry of an old growth coniferous forest watershed before and after cutting. Water Resour Res 17(5):1409–1418

Sollins P, Grier C, McCorison FM, Cromack K Jr, Fogel R, Fredriksen RL (1980) The internal element cycles of an old-growth Douglas-fir ecosystem in western Oregon. Ecol Monogr 50(3):261–285

Sollins P, Cromack K Jr, McCorison FM, Waring RH, Harr RD (1981) Changes in nitrogen cycling at an old-growth Douglas-fir site after disturbance. J Environ Qual 10(1):37–42
Stednick JD, Troendle CA, Ice GG (2004) Lessons for watershed research in the future. In: Ice GG, Stednick JD (eds) A century of forest and wildland watershed lessons. Society of American Foresters, Bethesda, pp 277–287
Stottlemyer R, Troendle CA (1987) Trends in streamwater chemistry and input-output balances, Fraser experimental forest, Colorado RP-RM-275. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins
Stottlemyer R, Troendle CA (1999) Effect of subalpine canopy removal on snowpack, soil solution, and nutrient export, Fraser Experimental Forest, CO. Hydrol Process 13:2287–2299
Swank WT (1988) Stream chemistry responses to disturbance. In: Swank WT, Crossley DA Jr (eds) Forest hydrology and ecology at Coweeta. Ecological Studies, vol 66. Springer-Verlag, New York, 339–357
Swank WT, Johnson CE (1994) Small catchment research in the evaluation and development of forest management practices. In: Moldan B, Cerny J (eds) Biogeochemistry of small catchments: a tool for environmental research. Scientific Committee on Problems of the Environment (SCOPE) 51. Wiley, Chichester, pp 383–408
Swank WT, Van Lear DH (1992) Multiple—use management: ecosystem perspectives of multiple—use management. Ecol Appl 2(3):219–220
Swank WT, Vose JM (1994) Long-term hydrologic and stream chemistry responses of southern Appalachian catchments following conversion from mixed hardwoods to white pine. In: Landolt R (ed) HydrologiekleinerEinzugsgebiete: Gedenkschrift Hans M. Keller. BeitragezurHydrologie der Schweiz 35.Bern, Schweizerische: SchweizerischeGesellschaft fur Hydrologie und Limnologie, pp 164–172
Swank WT, Waide JB, Crossley DA Jr, Todd RL (1981) Insect defoliation enhances nitrate export from forest ecosytems. Oecologia 51:297–299
Swank WT, Meyer JL, Crossley DA Jr (2002) Long-term ecological research: Coweeta history and perspectives Chapter 8. In: Barrett GW, Barrett TL (eds) Holistic science—the evolution of the Georgia Institute of Ecology (1940–2000). Taylor & Francis, New York, pp 143–163
Tilley DR, Swank WT (2003) EMERGY-based environmental systems assessment of a multipurpose temperate mixed-forest watershed of the southern Appalachian Mountains, USA. J Environ Manage 69:213–227
Triska FJ, Sedell JR, Cromack K Jr (1984) Nitrogen budget for a small coniferous forest stream. Ecol Monogr 54(1):119–140
Verry ES (1975) Streamflow chemistry and nutrient yields from upland-peatland watersheds in Minnesota. Ecology 56:1149–1157
Verry ES (1976) Estimating water yield differences between hardwood and pine forests. Research paper NC-128, USDA Forest Service, St. Paul, MN, 12 p
Verry ES (2004) Land fragmentation and impacts to streams and fish in the central and upper Midwest. In: Ice GG, Stednick JD (eds) Lessons for watershed research in the future: a century of forest and wildland watershed lessons. Society of American Foresters, Bethesda, pp 129–154
Verry ES, Lewis JR, Brooks KN (1983) Aspen clearcutting increases snowmelt and storm flow peaks in north central Minnesota. Water Resour Bull 19(1):59–67
Verry ES, Hornbeck JW, Todd AH (2000) Watershed research and management in the Lake States and northeastern United States. In: Ffolliott PF, Baker MB, Edminster CB, Dillon MC, Mora KL (eds) Land stewardship in the 21st century: the contributions of watershed management. Conference proceedings, Tuscon, AZ, 13–16 March 2000, USDA Forest Service, Fort Collins, CO, pp 81–92
Wells CG, Jorgensen JR (1975) Nutrient cycling in loblolly pine plantations. In: Bernier B, Winget CH (ed) Forest soils and forest land management, Fourth North American forest soils conference. Laval University Press, Quebec, pp 137–158
Wells CG, Jorgensen JR (1979) Effect of intensive harvesting on nutrient supply and sustained productivity. In: Leaf A (ed) Impact of intensive harvesting on forest nutrient cycling. State University of New York at Syracuse, USA, pp 212–230