

Chapter 17

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

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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

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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).

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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

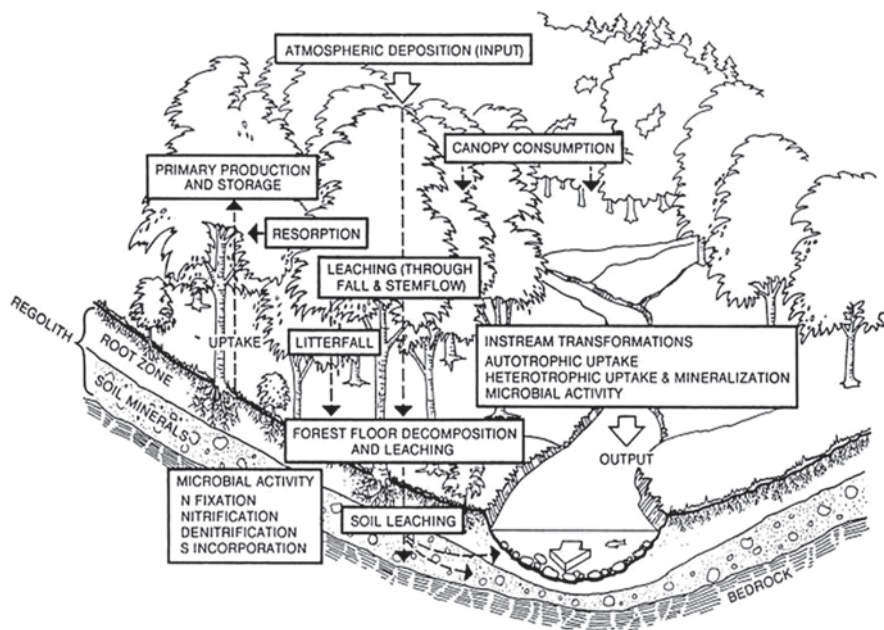


Fig. 17.2 Ecosystem components and processes regulating biogeochemical cycling in forest ecosystems

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 in 1984 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 (Stottlemeyer 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 San Dimas	UC-Berkeley	NADP	
	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 Stottlemeyer 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; Stottlemeyer 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

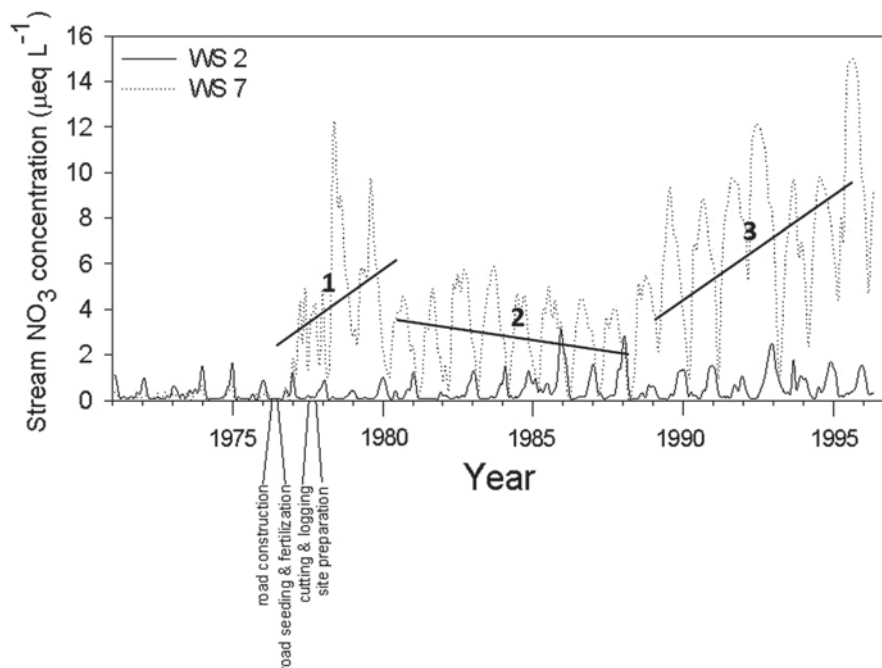


Fig. 17.3 Nitrate nitrogen concentration in stream water from a reference (*solid line, WS2*) and clearcut watershed (*dashed line, WS7*) at Coweeta. Three distinct trends in stream NO_3 were observed: 1=an increase in response to cutting and road bank fertilization, 2=a decrease in response to vegetation 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.

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