Chapter 13: Ecoregion 8.4.3 Western Allegheny Plateau: Fernow Experimental Forest, West Virginia

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Introduction

This chapter is a review and synthesis of research conducted at Fernow Experimental Forest (FER) on stream nutrients and biological responses. It is intended to inform national and regional water quality regulatory agencies, such as the U.S. Environmental Protection Agency, West Virginia Division of Forestry, and West Virginia Division of Natural Resources (WVDNR), about existing results of relevant scientific studies that are available at FER, and to identify future field and synthetic research of potential use to regulatory agencies that might be conducted at FER.

Site Description

FER is located within the Monongahela National Forest (MNF) near Parsons, West Virginia (lat. 39º 3' 15" N, long. 79º 41' 15'' W) (fig. 13.1). Vegetation at FER is dominated by a mixed-mesophytic-hardwood forest. Characteristic tree species include northern red oak (*Quercus rubra* L.), yellow-poplar (*Liriodendron tulipifera* L.), black cherry (*Prunus serotina* Ehrh. var. *serotina*), sugar maple (*Acer saccharum* Marshall), sweet birch (*Betula lenta* L.), red maple (*A. rubrum* L.), and American beech (*Fagus grandifolia* Ehrh.).

The topography of FER is mountainous with elevations ranging from 530 to 1115 m. FER encompasses most of Elklick Run watershed, a fourth-order tributary of the Black Fork of the Cheat River. Streams are generally steep, with shallow pools separated by riffles over bedrock ledges and gravel and cobble substrates. Elklick Run, which is the main stream draining the FER, feeds the Cheat and Monongahela River systems, flowing north to join the Ohio River at Pittsburgh. Thus, the FER is within the Mississippi River drainage basin.

Almost all exposed rocks in FER are sedimentary (Core 1966). The vicinity of the FER has not been glaciated. The predominant bedrocks on the western side of FER are from the Upper Devonian Hampshire Formation and are generally sandstones and acid shales that weather into relatively shallow soil (~1 m in depth to bedrock) with low supplies of base cations. Soils from this formation include the Dekalb and Calvin soil series (loamy-skeletal, mixed mesic Typic Dystrudepts). On the eastern side of FER, soils are derived from the Middle Mississippian Greenbrier

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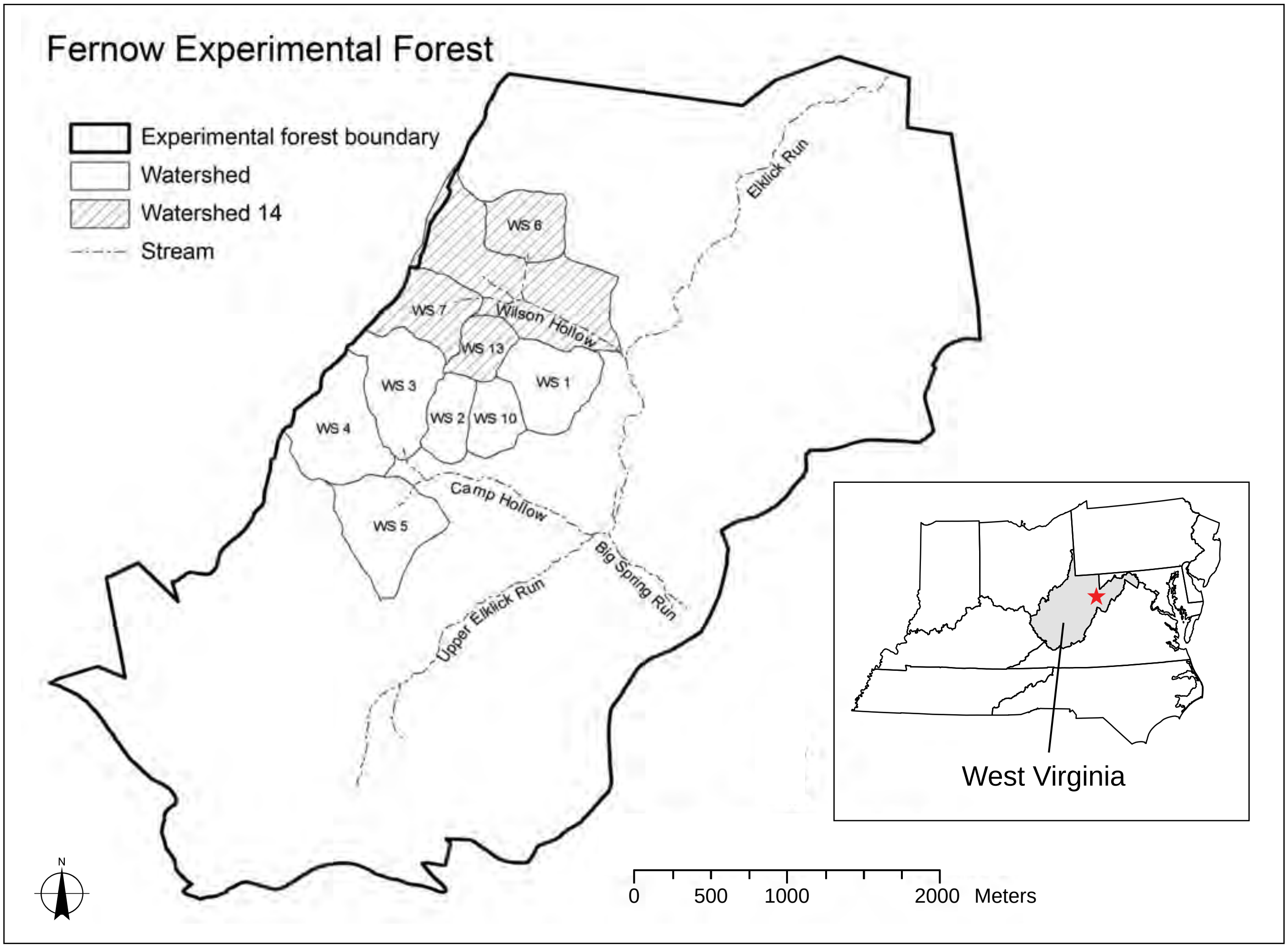

Figure 13.1—Fernow Experimental Forest with study watersheds (WS) and main-stem streams.

Limestone and Mauch Chunk formations that develop soils with higher productivity, notably the Belmont silt loam (fine-loamy, mixed, active mesic Typic Hapludalf) and the Cateache series (loamy, mixed active, mesic Ultic Hapludalf). Early researchers wished to conduct water balance studies using surface flows, so they located the study watersheds at FER on its western side, to avoid limestone bedrock with porous karst topography on its eastern side.

The growing season is May through October with an average total frost-free period of 145 days. Mean annual temperature is 9.2 °C. Precipitation is distributed evenly throughout the year, and averages 1480 mm annually. Snow contributes about 14 percent on average of precipitation at FER (Adams et al. 1994), and, although snow is common in winter, snowpack usually lasts no more than a few weeks. Hurricanes can cause large rainfall events in the summer and fall, but about half of the largest storms at FER have occurred during the dormant season from November 1 through April 30 (Adams et al. 1994) when streams are most responsive to rainfall because evapotranspiration is low.

Research History

The land for the FER was purchased by the federal government in 1915 and was the first tract of land acquired to form the MNF. The FER was established in 1934, setting aside for research and demonstration an area that is currently 1902 ha. FER was named after Bernhard Fernow, an early advocate of scientific forestry. The land use history has been well-described by Trimble (1977) and Kochenderfer (2006). Only about 1 percent of the area was historically converted from forest to other land uses, although most of the land that became FER was logged before 1920.

The earliest research on the FER focused on thinning and crop tree release efforts to facilitate recovery of the landscape altered by logging and associated fires that occurred from 1880 to 1920. Research operations were suspended in 1941, during World War II, and reinitiated in 1948 when silviculture and watershed studies were added (Adams et al. 2012).

Research on the FER has since followed those two lines of study, with considerable overlap. Silvicultural research has focused on managing mixed-hardwood stands, and addresses questions relating to regenerating, growing, tending, and harvesting trees and stands. Watershed research has addressed basic questions about water use by forests and forest hydrology, as well as issues about the effects on water and soil resources of forest management, roads, and best management practices.

The FER has been the site of groundbreaking research investigating the effects of acidic deposition and nitrogen (N) saturation on forest nutrient cycling. In particular, the FER is host to one of two U.S. studies evaluating effects of experimental whole-watershed acidification; the other is located at Bear Brook watersheds in Maine. The Fernow Watershed Acidification Study (FWAS) began in 1989 and involves experimental annual application of ammonium sulfate ($[NH_4]_2SO_4$) fertilizer to one watershed in a paired watershed design, with a second, untreated reference watershed. The Fernow Long-Term Soil Productivity (LTSP) Study has also evaluated nutrient cycling in a long-term experiment adding $(NH_4)_2SO_4$ fertilizer to 0.2-ha plots.

Long-term environmental monitoring to support research has been performed at FER for many years. Streamflow has been measured from five gaged, forested watersheds beginning in 1951 and stream chemistry beginning in 1971. Currently, a total of 10 watersheds are monitored both for flow and stream water chemistry (fig. 13.1). Meteorological data have been collected since 1951, and atmospheric deposition chemistry has been monitored as part of the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) since 1978. Permanent forest vegetation growth plots monitor net primary productivity of forest vegetation in long-term ecological studies.

FER has been part of the ongoing Long-Term Trout Monitoring Project (LTTMP) conducted in cooperation with West Virginia University, WVDNR, MeadWestvaco Corp., and MNF and Northern Research Station of the U.S. Forest Service (USFS). The LTTMP was initiated in 2003 on 25 headwater streams throughout the mountainous regions of West Virginia, including Elklick Run within FER. Annual measurements include physical characteristics of stream habitat, stream chemistry, and populations of stream fishes, with particular attention paid to the native brook trout (*Salvelinus fontinalis* Mitchill). Data have been used for monitoring and managing stream resources by WVDNR and MNF as well as for academic research (Hartman and Andrews 2014).

Availability of publications and data—
Meteorological and streamflow datasets can be downloaded from the FER website (USDA FS 2017a). Long-term FER daily streamflow and meteorological data, in formats suitable for ready comparisons with numerous long-term ecological research sites and other experimental forest research sites, are available at the ClimDB/HydroDB website (LTER Network 2013). The FER also participates in the NADP/NTN Networks, and those data on atmospheric deposition are available online from NADP (2019) and USEPA (2017). Real-time, provisional data for climate and some stream variables can be accessed via the FER SmartForests Network (SmartForests 2015). Other data may be available upon request to scientists at the FER.

More than 1,000 publications of research on the FER, from 1949 to the present, are publicly available, either through TreeSearch (USDA FS 2017b), or from the FER staff upon request. For a list of publications, see USDA FS (2017c).

Biological Responses to Stream Nutrients N and P

Issues of Concern

Because waters in the central Appalachians drain to the Chesapeake Bay and the Ohio/Mississippi River/Gulf of Mexico system, concern about nutrient loading and eutrophication of these coastal waters is of national significance. Both of these coastal waters have experienced low-oxygen dead zones with loss of marine life as a result of N loading from their watersheds.

More locally, there are concerns about impacts of forest land management on water quality and the health of stream ecosystems in the central Appalachians. Forest management is an important economic activity in this region, and there is considerable interest about the effects of forest management practices, including harvesting, prescribed fire, and fertilization, on nutrient exports, sediment production, and productivity and health of forest ecosystems, including streams. Of particular concern in aquatic ecosystems are impacts of land management on the health and productivity of native brook trout fisheries. The effects of forest harvesting on flooding has also been a recurring issue in the region.

Another concern in the central Appalachians is the availability of sources of reliable and high-quality drinking water, especially for small, rural communities that depend on forested headwater basins for their drinking water. Nutrient enrichment can degrade the quality of source water for drinking water systems.

Residential development at the wildland-urban interface may contribute N and phosphorus (P) to surface water from lawn runoff and septic system leaching. Such development in this region is often preferentially located near desirable waterfronts of sensitive streams and lakes.

Findings From Studies

FER research has contributed significantly to understanding nutrient cycling in watersheds and nutrient and sediment inputs to streams in small forested headwater watersheds. However, research on effects on stream biota has been less extensive. Studies evaluating the relationship between stream biota and habitat during the 1990s and early 2000s provide baseline data and may have implications for monitoring biological responses to water quality.

Stream chemistry has been monitored weekly at the outlets of most of the gaged watersheds at the FER since 1971, and these data have been used for indepth research on N cycling in watersheds. Research on the FER has documented significant leaching of nitrate (NO_3^-) from these forested watersheds, which is at least partially due to high levels of acidic deposition (Adams et al. 2007, Edwards and Helvey 1991, Peterjohn et al. 1996). Historically, wet deposition of N was as high as 10 kg N/ha/yr, but has declined since 2000. Between 2004 and 2014, atmospheric inputs averaged 4.8 kg N/ha/yr in wet deposition, plus dry deposition of 1.1 kg N/ha/yr (USEPA 2017). Consistent with these high rates of N deposition, stream water NO_3^- concentrations are also high at FER, averaging 840 ug NO_3^--N/L (2004–2006), with exports of dissolved inorganic nitrogen (DIN) estimated to be 6.2 kg N/ha/yr (2006–2010) (Adams et al. 2014). Stream water NO_3^- levels from undisturbed watersheds at FER have increased almost threefold from the early 1980s to the present (Adams et al. 2014, Argerich et al. 2013, Campbell et al. 2004, Jones et al. 2012, Peterjohn et al. 1996). Stream water NO_3^- concentrations and leaching from some FER watersheds have been much greater than reported for other research forest watersheds in the Eastern United States (Argerich et al. 2013, Campbell et al. 2004). No studies have investigated whether stream biological communities at FER have changed in response to changes in ambient levels of stream NO_3^- since the 1980s.

Results of the FWAS (Adams et al. 2006) demonstrated that chronic $(NH_4)_2SO_4$ additions to a whole watershed to simulate elevated acidic deposition produced acidification of stream water, significant leaching of NO_3^- from the watershed, and elevated soil and stream water NO_3^- concentrations (Adams et al. 2006, 2007). Each year since 1989, $(NH_4)_2SO_4$ has been added to this watershed to increase N loading to the soil surface two times above ambient loading, as measured in 1988 (Helvey and Kunkle 1986). Stream water NO_3^- concentrations in the treated watershed are at least threefold greater than those in the reference watershed (2000–2014), and exports of N from the treated watershed are similarly higher. The peak stream NO_3^- concentrations in the treated watershed have approached the U.S. drinking water standard of 10 mg NO_3^--N/L.

Experimental additions in the FWAS of $(NH_4)_2SO_4$ also acidified stream water (from pH 6.0 to about pH 5.0 over 25 years). Work at the Bear Brook watershed in Maine, the other watershed acidification study in the United States, provides evidence that stream water acidification can result in increased abiotic sorption of P by aluminum (Al) and iron (Fe) hydroxide, and limited P availability to stream organisms (Mineau et al. 2014, Simon et al. 2010). At the Bear Brook watershed, P bound to Al on leaf litter was not as available for microbial use, which may reduce stream productivity. Leaf litter in streams was a significant abiotic sink for P, suggesting that leaf litter inputs in the autumn may play a large role in the regulation of P availability (Simon et al. 2010). Increased nutrient excretion by invertebrate consumers was found when macroinvertebrate larvae were fed P-enriched leaves, suggesting P limitation. Experimentally elevated stream water N levels did not significantly stimulate N uptake by microbes in streams, possibly because of the concurrent suppression of microbial activity by stream acidification, or because N was not limiting. From these findings, we infer that under ambient (nonfertilized) conditions in FER streams, N and P are probably rapidly cycled and exported but are not biologically assimilated, perhaps partially owing to stream acidification by atmospheric deposition.

Many aspects of N cycling have been studied at FER. Efforts by Hom et al. (2006) to model the relationship between stream water NO_3^- levels and N deposition at several spatial scales, based in part on FER findings, however, were not able to reproduce trends in measured stream water NO_3^-. Other scientists using N-cycling process models have had similar experiences in trying to model FER results.

From comparisons with other regions, N cycling at FER appears to have characteristics that are different from most other forested watersheds that have been studied (Argerich et al. 2013, Campbell et al 2004). For example, stream water NO_3^- levels are consistently higher at FER than at Hubbard Brook Experimental Forest (HBEF) (chapter 3) and Coweeta Hydrologic Laboratory (CHL) (chapter 14). Stream export of N (6.2 kg N/ha/yr) has been roughly equal to total atmospheric deposition of N (~5.5 to 7.5 kg N/ha/yr) from minimally disturbed FER reference watersheds.

At both HBEF and CHL, annual N exports have been significantly less than total atmospheric deposition, as is typical of most forests. Furthermore, since the late 1980s, stream water concentrations of NO_3^- at FER have not tracked trends in atmospheric deposition of N. Stream water NO_3^- at FER significantly increased over time while total atmospheric deposition of N has declined slightly. In roughly the same period, at HBEF stream water NO_3^- concentrations decreased as did atmospheric deposition of N, and, at CHL, stream NO_3^- increased along with rising N deposition (Adams et al. 2014, Argerich et al. 2013).

One hypothesis that may explain the characteristics of the N-cycle at FER is that the forest at FER may have become N saturated (Fenn et al. 1998, Peterjohn et al. 1996). According to this theory, high levels of chronic N deposition that continued for decades at FER have filled, or "saturated," forest vegetation and soils to capacity. A watershed that is saturated with N loses its ability to accumulate added N, causing both stream export of N, and stream water concentrations of NO_3^- to rise (Aber et al. 2009).

Although evidence exists that supports the N-saturation hypothesis, not all of the predicted outcomes have been observed on the FER. For example, the N-saturation theory (Aber et al. 2009) predicts that N should no longer be the limiting nutrient in an N-saturated ecosystem, but clear evidence has been elusive as to what nutrient is currently limiting terrestrial and aquatic productivity under current levels of N deposition at FER. Gress et al. (2007) found changes in P availability in soil of a watershed at FER fertilized with $(NH_4)_2SO_4$, suggesting that P may be limiting to vegetation when nitrogen limitation was experimentally removed. However, studies under ambient levels of N deposition at FER, with no fertilizer additions, have not yet determined what nutrient is limiting to growth of upland vegetation, and although P might be limiting in streams, it has not been monitored in stream water at FER.

Although long-term trends in NO_3^- concentrations from other forested watersheds within the central Appalachians and western Allegheny Plateau are not available, data do exist to place FER watersheds in context. Williard et al. (2005) reported that FER reference Watershed (WS) 4 was among the top 10 percent of the watersheds surveyed in Pennsylvania, Maryland, and West Virginia, when ranked on NO_3^--N concentrations. In a more localized stream NO_3^- survey within 10 km of FER, nearly half of the 27 streams sampled had stream NO_3^- concentrations greater than FER WS 4. Both of these studies suggest that nitrogen saturation may be a relatively common condition within the region.

Although levels of stream NO_3^- concentrations have been documented across the mid-Appalachians (DeWalle et al. 1988; Williard et al. 2003, 2005), the mechanisms controlling stream water NO_3^- levels are not well-understood. For example, the role of bedrock geology in controlling the N cycle of forests is not well-understood. Does N cycling in limestone geologies resemble that documented in the FER's more acidic sandstone and shale bedrock? Williard et al. (2005) found that bedrock geology explained the most variation in stream NO_3^- concentration of 49 mid-Appalachian watersheds, but that other soil and vegetation characteristics are also correlated with stream NO_3^- levels.

Other Factors Relevant to Stream Nutrients N and P

A variety of habitat and environmental factors have been monitored or studied at FER that may affect biological responses to N and P. For example, streamflow in the central Appalachians is very responsive to precipitation events (Kochenderfer et al. 2007, Reinhart et al. 1963). Long-term monitoring of precipitation, temperature, and streamflow has provided information that allows assessment of the role of these variables on stream chemistry. As chemical constituents of stream water vary, the responses of stream biota will also vary.

Studies of stream biological communities at FER have largely focused on stream habitat as a factor controlling distribution and structure of aquatic communities. Although these studies did not explicitly investigate biological responses to stream levels of N and P, many were conducted in streams in which background conditions, including stream water nutrient concentrations and streamflow, were routinely monitored. Below is a brief description of each of these studies.

The abundance, life history, and production of the stoneflies *Peltoperla arcuata* and *Tallaperla maria* were examined in four forested headwater streams with different stream chemistry at the FER (Yokum et al. 1995). Abundance of *P. arcuata* was highest in the smallest watersheds (<100 ha) and was present at all sites. Abundance of *T. maria* was highest in streams draining watersheds >200 ha, was restricted to reaches with a baseflow alkalinity of >2 mg calcium carbonate ($CaCO_3$)/L, and was the dominant peltoperlid only at sites with an alkalinity >15 mg/L. An important conclusion was that water chemistry was more important than stream size as a determinant of distribution of some peltoperlid species on the FER.

Angradi (1996) investigated the role of physical habitat in benthic community structure and function in three headwater streams. Mass of benthic organic matter was greatest in debris-dam pools and was dominated by coarse particles and wood. Mean animal density (macroinvertebrates and salamander larvae) was highest in debris-dam pools and on rock faces and lowest in riffles and plunge pools. The biomass of animals was highest in pools and lowest in riffles and on rock faces. Functional organization differed among habitats. In riffles, all functional groups were well represented. Scrapers, filterers, and gatherers predominated on rock faces. In pools, shredders and predators dominated biomass, although gatherers were the most abundant group. In plunge pools, crayfish (*Cambarus* sp.) were relatively more abundant than in debris dam pools; but the opposite was true for macroinvertebrate predators. Overall, within-stream variability in structure, abundance, biomass, functional organization, and benthic organic matter exceeded the variability among streams.

Vertical, longitudinal, and seasonal variation in the abundance, taxa richness, and community composition of the epibenthic and hyporheic macrobenthos were examined for a first- through fourth-order stream continuum along Elklick Run on the FER (Angradi et al. 2001). Abundance, relative abundance, and taxa richness of streamlined taxa decreased with depth (to 30 cm) into the substratum. Abundance and taxa richness varied more with depth into the substratum than among sites or among seasons. However, both epibenthic and hyporheic community structure varied much more among seasons than among locations or among depths. The amount of variability in hyporheic abundance, taxa richness, and community composition decreased as stream order increased.

Angradi (1999) also examined the effects of benthic fine sediment on macroinvertebrate assemblages by experimentally varying fine sediment (<2 mm) between 0 and 30 percent in otherwise natural substratum at each of three sites along Elklick Run on the FER. Effects of fine sediment on macroinvertebrate density, biomass, and species composition metrics were generally subtle, even when statistically significant. Assemblage structure was altered by the amount of fine sediment, but the shift was generally less than the variation among the three sites.

Stream physical habitat data from the LTTMP showed consistent patterns in the amount of each instream habitat type from year to year, although within habitat types there were some trends. While depth of pools and average depth of habitat units remained consistent for most of the first decade of study, dramatic changes recently occurred from the heavy additions of large woody debris (LWD) to many of the study streams caused by Super Storm Sandy in October, 2012. The additions of LWD differed considerably among streams. Elklick Run within FER had the greatest additions of LWD within the network of monitored streams (Andrews and Hartman 2015).

Brook trout populations on the FER typically showed only minor fluctuations over 10+ years of the LTTMP study. Hartman and Andrews (2014) interpreted these stable population sizes as a sign that native brook trout were near their full potential in these small, headwater streams.

Climate change is another factor that may influence response of stream biota to nutrients. Long-term stream water and air temperature data have been collected on FER watersheds. Mean annual air temperatures have significantly increased by ~0.3 °C since 1951 on the FER (Vose et al. 2011), and although FER stream water temperatures might logically have also increased, no analyses of FER stream temperature data have yet tested that supposition. Summer streamflows from WS 4 have also significantly increased over that period (Jones et al. 2012), perhaps in response to changes in precipitation, but that relationship has not been thoroughly investigated.

Reference Watersheds

Three reference watersheds on the FER have been managed for minimal human disturbance. Watershed 4 is the oldest and largest, with 38.7 ha, and its stream outlet has been gaged since 1951. Watershed 10, with 15.2 ha, and WS 13, with 14.2 ha, have been gaged since 1984 and 1988, respectively. Starting in the early 1950s, scientists established meteorological and air quality monitoring to support the research on the reference watersheds. Nitrogen cycling has been studied on all three reference watersheds and most extensively on WS 4 (Christ et al. 2002, Peterjohn et al. 2015).

These watersheds have been used as untreated references against which to compare effects of experimental treatments such as forest harvesting, fertilization, and other management to discern their effects on streamflow, stream chemistry, soil properties, and vegetative productivity. For example, Patric (1973) quantified effects of deforestation treatments on soil moisture, streamflow, and water balance by comparing the response of a treated watershed with untreated reference WS 4.

In addition, these reference watersheds have also been important study sites in their own right because they represent ecological conditions in well-documented, undisturbed, forested headwater basins in the central Appalachians. The reference watersheds are vegetated with second-growth forest stands last harvested around 1910. Although they may not represent true old growth, they have been managed for minimal human disturbance since FER was established. Forested lands in the central Appalachians were extensively harvested in the early 1900s, so this disturbance history is similar to that of most mature forests in this region. The vegetation composition and growth on these reference watersheds have been monitored using permanent tree growth plots (Adams et al. 2012), and soil chemistry has been monitored using repeated sampling.

Stream water chemistry has been monitored weekly at the outlets of all three FER reference watersheds for NO_3^- and NH_4^+, since 1971, and dissolved organic nitrogen (DON) and dissolved organic carbon (DOC) starting in 2016. As we described earlier, stream water NO_3^- levels from these undisturbed watersheds have increased significantly from the early 1980s to the present (Adams et al. 2014, Argerich et al. 2013, Campbell et al. 2004, Jones et al. 2012, Peterjohn et al. 1996) despite decreasing wet plus dry N deposition over that period. Watershed 4 has often been described as a clear example of a N-saturated watershed (Fenn et al. 1998, Peterjohn et al. 1996). Regardless of what theory may explain their stream nutrient behavior, these watersheds provide evidence that stream water quality has not remained static in these reference streams despite well-documented management to minimize onsite human disturbance of these watersheds.

Cross-Site and Regional Studies

The FER has a long history of participating in cross-site studies (see for example, Argerich et al. 2013, Campbell et al. 2004, Hornbeck et al. 1993, Reinhart et al. 1963). FER has most often been compared with HBEF and CHL, which lie north and south, respectively, of FER, along the Appalachian chain. Streamflow and hydrologic processes have been compared among these three sites, and other sites across the United States to investigate effects of climate on streamflow (Adams and Kochenderfer 2014, Hornbeck et al. 1993, Jones et al. 2012). As was described earlier, N dynamics at FER have differed significantly from those at HBEF and CHL as well as most other forests studied in the Eastern United States (Adams et al. 2014, Argerich et al. 2013, Campbell et al. 2004). Atmospheric deposition data from FER have been used in annual regional and national analyses and maps of atmospheric deposition produced by the NADP, which have shown that N deposition has been higher in the vicinity of FER than most other areas in the Eastern United States.

Responses to Management and Natural Disturbances

FER watershed research has evaluated the effects of a variety of forest management activities on streamflow and water quality over the long term. Research on timber harvesting effects began in 1951 (Reinhart et al. 1963). These early studies focused mostly on sediment and water yields. Results, comparing four harvesting treatments without standard best management practices (BMPs), demonstrated that (1) at least 25 percent of the tree basal area of a watershed had to be harvested to produce a measurable increase in annual streamflow, (2) annual streamflow increased proportionally to the basal area removed above the 25 percent threshold, (3) most of the annual streamflow increases occurred during the growing season because of decreased evapotranspiration after harvesting, and (4) even the most extreme streamflow increases were generally short lived because of rapid regrowth of vegetation (Adams and Kochenderfer 2014, Reinhart et al. 1963). Annual streamflow also increased significantly following a commercial clearcut, as did turbidity. Both streamflow and turbidity then decreased to pretreatment levels within 4 to 6 years after cutting (Reinhart et al. 1963). Similar results have been reported over longer time periods and in comparison with a number of other watershed research sites (e.g., Hornbeck et al. 1993, Jones and Post 2004). Stream water conductivity increased after clearcutting followed by suppression of vegetation on the watershed using herbicides, but these effects declined to pretreatment levels in less than 10 years after herbicide ceased, owing to rapid revegetation (Kochenderfer and Wendel 1983).

Kochenderfer et al. (2007) investigated the largest stormflows from the FER to evaluate the causes of flooding. Total storm precipitation and average storm precipitation intensity were the most significant variables affecting peak flows and were far more important than timber harvesting activities in affecting peak flows.

Research on the FER demonstrated that the largest source of sediment to streams during forest management activities came from unpaved forest roads. Scientists at the FER were involved in developing methods of road planning and construction that could reduce erosion and sedimentation (Kochenderfer and Helvey 1984, 1987), and in transferring that knowledge to land managers. FER scientists helped develop many West Virginia forestry BMPs and have worked to develop protocols for evaluating the effectiveness of BMPs regionally and nationally. The West Virginia forestry BMPs do not deal specifically with management effects on stream nutrients or biological responses to them.

Experimental treatments of FER watersheds with the insecticide Dimilin that simulated control measures for gypsy moth produced mixed effects on stream invertebrate densities. Some taxa decreased or remained unchanged in treated watersheds relative to streams in reference watersheds, whereas other taxa increased. Taxa with reduced mean densities in treatment watersheds included the stoneflies, *Leuctra* sp. and *Isoperla* sp., the mayfly, *Paraleptophlebia* sp., and the crane fly, *Hexatoma* sp. Mean densities of shredders, the dominant functional feeding group, also decreased in treated watersheds. Densities of Oligochaeta and Turbellaria increased in streams in treated watersheds (Hurd et al. 1996). Soil and leaf litter invertebrates showed no significant effects from Dimilin treatment (Perry et al. 1997).

Several studies in the 1970s and 1980s assessed forest fertilization with urea or NH_4NO_3 plus triple superphosphate in mixed-hardwood forests, and its effects on stream chemistry. Regardless of the type of N fertilizer applied, approximately 20 percent of N was exported during the initial 2 to 3 years (Aubertin et al. 1973, Edwards et al. 1991, Patric and Smith 1978). Stream water concentrations of NO_3^- were fairly low (maximum of 4.86 mg NO_3^--N/L) and did not exceed public drinking water standards (Aubertin et al. 1973). A single large application of NH_4NO_3 fertilizer significantly increased stream water NO_3^- concentrations (Helvey et al. 1989); however, levels decreased after 3 years to pretreatment levels. No changes in phosphate concentrations of stream water occurred in response to P fertilization (Edwards et al. 1991). Stream biological responses to nutrients were not studied in these fertilization experiments.

Natural disturbances to forests at FER include blowdown, insects and diseases that attack trees, wildland fires, and floods. Relatively little research at FER has evaluated effects of natural disturbances on stream N and P or biological communities. Wind damage to trees from Super Storm Sandy in 2012 resulted in large inputs of dead wood to streams, likely altering stream physical habitat (Andrews and Hartman 2015). Chestnut blight, Dutch elm disease, and other introduced pests and pathogens have historically caused tree mortality in the FER forest, but the effects of these disturbances on stream water nutrients have not been evaluated. Wildland fires were historically recurring disturbances, with large fires in the aftermath of widespread logging in the early 20th century. Fire suppression since the 1930s has effectively excluded wildland fires from FER and in most of the region. Prescribed fire is increasingly used in the region to manage stand species composition and to reduce fuel accumulations. Research on prescribed fire is a relatively new area of experimentation at FER.

Angradi (1997) studied responses of aquatic macroinvertebrates to two floods at FER with recurrence intervals of 18 and 12 years, in February and May 1994, respectively. Benthic organic matter, macroinvertebrate abundance, and community structure were affected by the floods, but recovered quickly. Immediately following the February flood, abundance of most of the common macroinvertebrate taxa decreased by 70 to 95 percent. Riffle taxa were affected more by the February flood than were taxa associated with organic matter accumulations such as leaf packs and organic debris dams. Recovery to preflood levels of most physical and biotic variables was complete before the May flood. By August, following the May flood, few differences could be detected from August of the previous year. Shifts in community structure following floods were small compared to seasonal variation. These results indicated that the stream macroinvertebrate community was strongly resilient after flood disturbance. Stream biological responses to natural disturbances, other than floods, have not been studied at FER.

Reliability and Limitations of Findings

FER long-term data are of high quality and were collected with documented quality assurance/quality control protocols (Edwards and Wood 1993). Data on stream biota are short term because they were mostly collected to test specific research hypotheses rather than for long-term monitoring. Datasets and research results from FER probably apply to most forested headwater basins in the central Appalachians with similar bedrock (Williard et al. 2005) and that have not had mining or other severe disturbance. At locations with geology or land use dissimilar to FER, or, if a high degree of accuracy is required, users might consider validation studies or monitoring to test how well results from FER predict local conditions.

Research Needs

From the perspective of the water quality regulatory community, the highest priority research question related to biological responses to N and P that might be addressed at FER is, How does stream water NO_3^- in central Appalachian forested headwater streams respond to changes in levels of atmospheric deposition of N? Answering this question could provide critical information for regulators because FER findings imply that, if acid and N deposition were to increase or continue unchanged in the future, forested watersheds in the central Appalachians could potentially become larger sources of stream NO_3^-. Study results from FER probably apply to forests within the Chesapeake Bay watershed because, although the FER is located a short distance outside of the bay watershed, it is in the same ecoregion and has vegetation, geology, and land use that are common to large areas of forests that drain to the bay. Increased stream NO_3^- from forest land might potentially compel water quality regulatory agencies to consider tighter restrictions on nonforest sources of stream water N, such as agricultural and urban areas, to prevent increased total N loading to the Chesapeake Bay. In addition, if increases in stream water NO_3^- were large enough, rural communities that depend on forest watersheds for their drinking water might experience increased NO_3^- concentrations in source water. Thus, for regulators, it will be important to understand how forests in the central Appalachians have responded to changes in ambient acid and N deposition to better understand and predict how forests might respond to deposition in the future.

Filling this research need at FER would require a reexamination of long-term data on trends in atmospheric deposition of N and stream water export of N that have been observed at FER. The objective would be to determine what degree of confidence there is in the existing scientific evidence for a relationship between atmospheric deposition and stream water NO_3^- export. If reanalysis finds areas of significant uncertainty, further analyses or experiments to narrow that uncertainty might be warranted. Once sufficient confidence in the underlying evidence has been established, models based on results of the FWAS and LTSP Study could be developed to estimate how stream water NO_3^- levels in forest streams might be expected to change under future scenarios of N deposition. Records of stream water N chemistry from forest streams in the central Appalachians outside of FER would also be examined to assess how widespread the N characteristics observed at FER are in the region and to determine to what geographic areas a model of stream water N response to N deposition, based on FER findings, might be applicable.

Other regional research needs that might be filled at FER, but of lower priority for regulators, include studies of effects of prescribed fire on water quality and quantity, further analysis of the role of forests and forest management in flooding, and better understanding of the role of P in the ecology of forest streams in the central Appalachians.

Potential Utility to Water Quality Regulatory Agencies

Long-term data from FER could be used by regulators to supply information about sediment and nutrient loading from undisturbed forested headwater streams, and about the effects of forestry activities in addressing total maximum daily load (TMDL) regulations relative to the Chesapeake Bay Program, for example. FER has an enormous amount of existing data and science findings about effects of forest management practices on streams, particularly relative to harvesting and roads, and to a lesser extent, fertilization. Scientists at the FER have contributed a significant body of work toward development of BMPs to minimize sediment export to streams, and this research might further be applied by regulatory agencies in developing, evaluating, and updating BMPs for forest practices.

FER has a wealth of existing data drawn from long-term hydrologic research (Adams et al. 2012) and indepth studies of some aspects of stream biology. Hydrologic data that are of high quality and defensible in a court of law are needed to address recurring issues by regulatory and land management agencies. Results of FER stream biological studies might be useful to regulatory agencies for designing future stream biological monitoring surveys.

In addition to informing regulations about local effects of logging on stream sediment, FER research results might also be used by regulatory agencies to represent effects of forest management on water quality from forested headwater basins in West Virginia and neighboring states. For example, these results could be used in models of the Chesapeake Bay drainage to assess inputs of nutrients and sediment to the estuary, as affected by land use. In general, effects of forest management are currently missing from these basin-scale models.

Key points:

- The existing long-term hydrological and climatological data from the FER are extremely valuable and useful to regulatory agencies.
- FER has studies and data on some limited aspects of stream biology. A synthesis of the available data may provide a starting point for a stream biological monitoring program.
- Much of the research on the FER has focused on harvesting effects on stream water quantity and quality, and on the effects of acidic deposition on stream levels of N.
- The research question of highest priority for the regulatory community that might be answered at FER is, How does stream water NO_3^- in central Appalachian forested headwater streams respond to changes in levels of atmospheric deposition of N?
- Future work to address the highest priority question at FER might include a reanalysis of existing FER datasets and developing models based on results of the FWAS to predict the response of stream water NO_3^- from forested watersheds to future changes in N deposition.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Although emissions of sulfate (SO_4^{2-}) have been declining in the eastern United States, atmospheric deposition of SO_4^{2-}, in combination with deposition of N, is expected to continue as a substantial contributor to surface-water acidity in the central Appalachians for the immediate future. This prospect raises concerns about effects on watershed acidification, stream chemistry, and biota. Specifically, acidic deposition can produce levels in soil and in stream water of acidity, calcium (Ca), magnesium (Mg), and Al that are detrimental for various organisms. Low pH, for example, can cause elevated levels of dissolved Al in soil solution and stream water, which are toxic to aquatic organisms such as brook trout, as well as to plant roots. Decades of high SO_4^{2-} deposition have been absorbed by soils, and as SO_4^{2-} deposition has decreased, accumulated SO_4^{2-} may desorb from soil surfaces, resulting in elevated leaching of SO_4^{2-} to streams, contributing to continued stream acidification. Brook trout, a favorite among sport fishers in the region, are particularly sensitive to stream water acidity and usually cannot survive chronic exposure below pH 5.5.

Regionally, there is also concern that long-term acidic deposition may have depleted base cation weathering potential in soils, reducing watershed buffering capacity and making streams more vulnerable to the acidifying effects of atmospheric deposition (McDonnell et al. 2012). This process might extend acidification to additional headwater streams and to reaches farther downstream that were previously buffered.

Erosion and sedimentation are also a significant water quality issue. Erosion, with subsequent deposition of sediment in waterbodies, moves nutrients in soil from terrestrial ecosystems to aquatic ecosystems. Land management activities can significantly affect water quality through elevated rates of erosion and sedimentation. The increased use of prescribed fire in the region is a concern for forest land managers, particularly related to erosion and sedimentation. The recent expansion of exploration and development of shale gas in the region has raised concerns about effects of sediment, nutrients, and other pollutants from these activities on water quality and aquatic organisms.

In some parts of the Appalachians, mining of coal and leaching from acid spoils have produced degraded stream water quality, particularly low pH, high levels of SO_4^{2-}, and toxic levels of metals, including Fe, manganese (Mn), and Al, along with erosion and sedimentation. FER has not had mining or spoil disposal, so its streams represent the background conditions in forested headwaters in the absence of mining disturbance.

There are also concerns that climate change may affect nutrient cycling rates, and the health of stream biota, both through direct effects such as changes in stream temperature and precipitation patterns, and indirectly through changes in terrestrial carbon cycling, which may affect energy available to stream food webs.

Findings From Studies

Monitoring of stream water and precipitation chemistry at FER has also proved useful for understanding biogeochemical cycling of elements other than N and P, in particular, sulfur (S), Ca, and Mg. Helvey and Kunkle (1986) developed the first input-output nutrient budgets for the FER for WS 4. They reported that SO_4^{2-} inputs in precipitation exceeded outputs in stream water, and also observed net loss of Ca and Mg via stream water. DeWalle et al. (1988) developed a more detailed biogeochemical budget for WS 4, which corroborated these results.

Results from FWAS have documented that SO_4^{2-} adsorption to soil particle surfaces has continued after more than two decades of $(NH_4)_2SO_4$ additions, and that leaching of Ca and Mg was accelerated in response to the acidification treatment (Adams et al. 2006, 2007). Stream water pH decreased in the treated watershed from 6.0 to around 5.5, a level that is critical for brook trout. Acid neutralizing capacity (ANC) of stream water initially increased in response to watershed fertilization, then decreased as Ca and Mg were depleted from the soil by leaching. The LTSP

Study at FER investigated whether Ca was limiting forest vegetation production (Adams et al. 2004, Fowler et al. 2015), but significant signs of limitation owing to Ca were not detected.

A few FER studies on stream biota provide baseline information relative to biological response to acidity and nutrients other than N and P, in particular, looking at varying levels of stream acidity as measured by pH. Leaf litter processing rates and macroinvertebrate shredder assemblages in leaf packs were compared in four streams of differing acidity on and near the FER. These streams had different bedrock geology that produced ambient mean stream water pH of 7.5, 6.1, 6.0, and 4.3. The crayfish *Cambarus bartonii* contributed >55 percent of shredder biomass in all streams, but <20 percent of shredder production. Annual production of the other common shredder species differed among streams. Annual production of the shredder functional group ranged from 3.77 g dry mass/m^2 in the highest pH stream to 1.19 g dry mass/m^2 in the lowest pH stream. Higher densities of *Amphinemura* sp., *Leuctra* sp., *Eurylophella funeralis,* and *Paracapnia angulata* were characteristic of the stream with the lowest pH. Higher densities of *Peltoperla arcuata* and *Wormaldia moesta* were found in the streams with pH of about 6.0. *Gammarus minus, Baetis* sp., *Ephemerella dorothea,* and *Sweltsa* sp. were found at higher densities in the stream with a pH of 7.5 (Griffith et al. 1994, 1995). Leaf litter processing rates were fastest in the near-neutral streams, slowest in the acidic stream, and intermediate in the most alkaline stream. Dubey et al. (1994) found greater numbers of aquatic fungal taxa in streams on or near FER that were less acidic. Stephenson et al. (1995) reported that bryophyte species diversity and abundance decreased with decreasing pH. Although this study did not explicitly examine the effect of nutrients, ambient stream Ca and Mg levels often correlate with pH, so these results might also reflect biological responses to those nutrients.

Although stream pH did differ between the treated and reference watersheds in the FWAS, there were no significant differences in size, tail fat, or reproduction between the watersheds for the woodland salamanders *Plethodon cinereus* and *Desmognathus ochrophaeus* or *D. monitcola* (Pauley et al. 2006).

Other Factors Relevant to Biological Responses to Stream Nutrients Other Than N and P

As discussed previously, numerous studies and long-term monitoring datasets provide abundant information about other environmental factors that may also affect biological responses to nutrients other than N and P. Among these factors are streamflow, stream temperature, fine sediment in the substrate, and other habitat characteristics, including LWD inputs. Studies at FER of stream acidification and long-term climate variability suggest that these two factors may also affect availability of other nutrients, in particular Ca and Mg.

Cross-Site and Regional Studies

Recently, FER long-term data have been used, along with data from a large collection of experimental forest sites, to assess whether regional changes in climate have occurred (Vose et al. 2011), and to evaluate climate change effects on streamflow behavior (Creed et al. 2014, Jones et al. 2012). Kerr et al. (2011) used a collection of watersheds to evaluate the relationship between seasonal drought and SO_4^{2-} dynamics. They found a stronger relationship between peak SO_4^{2-} concentrations and seasonal drying for Canadian and northern U.S. watersheds than for more southern catchments such as the FER. Atmospheric deposition data collected at FER have been used by NADP in annual analyses and maps of regional and national wet and dry atmospheric deposition of SO_4^{2-} and additional elements other than N and P (NADP 2019).

Responses to Management and Natural Disturbances

The LTSP has experimentally manipulated aboveground biomass by using whole-tree harvesting and simulated acidic deposition using chemical additions to examine effects on upland carbon sequestration and cycling of Ca and Mg (Fowler et al. 2015). Although these treatments removed significant amounts of Ca and Mg in vegetative biomass and from soil exchange sites by leaching, they also significantly increased aboveground carbon storage. Soil solution concentrations of Ca and Mg collected below the rooting zone of treatments increased during the first 10 years.

Water quality parameters, which have been routinely monitored on watersheds that received different harvesting treatments, included pH, conductivity, ANC, SO_4^{2-}, Ca, Mg, potassium (K), sodium (Na), and chloride (Cl^-). Most of these stream water parameters were found not to be significantly altered in response to harvesting (Aubertin and Patric 1972). Responses of nutrients other than N and P to natural disturbances have not been studied at FER.

Reliability and Limitations of Findings

Datasets and research results from FER related to nutrients other than N and P probably apply to most forested headwater basins in the central Appalachians with underlying geology and land management similar to FER study watersheds. However, if a high degree of accuracy is required, or at locations with land uses or geology dissimilar to FER, validation studies or monitoring might be useful to test how well results from FER predict local conditions.

Reference Watersheds

Water quality parameters (other than N and P), which are routinely monitored at the stream outlets from all three FER reference watersheds, include pH, conductivity, ANC, SO_4^{2-}, Ca, Mg, K, Na, and Cl^-. Long-term trends have been analyzed for these stream water chemical constituents in reference watershed streams. Long-term annual export of Ca has increased for WS 4 from the 1970s to the present, and leaching of Ca from the soil is mostly linked with increased NO_3^- export and, to a lesser extent, SO_4^{2-} export (Adams et al. 2007, 2014; Peterjohn et al. 1996). The three reference watersheds differ with respect to SO_4^{2-} export (Peterjohn et al. 2015).

Research Needs

The highest priority research question for regulators related to nutrients other than N and P that could be addressed at FER is, How do the effects of acidic deposition and land management activities combine to alter stream acidification? Answering this question would be important to the regulatory community because it would help inform decisions regulating forest land management activities in watersheds that are sensitive to stream acidification from atmospheric deposition. For example, this information might help regulatory agencies to better understand how forest management activities and acidic deposition may combine in sensitive watersheds to accelerate or ameliorate base cation depletion of soil, and its ramifications for stream acidification. Such information might be useful for developing forest management permitting regulations that better protect trout streams at risk from acidification.

Future work that would be required to answer this question at FER would include developing process models of stream acidification that can be extrapolated to larger areas and watersheds. This would entail developing or validating models that include details of SO_4^{2-}, Ca, and Mg cycling, based upon detailed analyses of data from the FWAS and the LTSP Study. An objective of this research would be to establish clearer linkages between soil, watershed, and stream cycling of SO_4^{2-}, Ca, and Mg, and their effects on stream acidity that are critical to aquatic biota. Included in this research would be related studies on mineral weathering rates and carbon cycling in these systems.

Another research need that might be filled at FER, although of lower priority for the regulatory community, would be development of a better understanding of how changes in land uses, for example, increased prescribed fire or natural gas development, might alter erosion and sedimentation within forested watersheds in the central Appalachians.

Potential Utility to Water Quality Regulatory Agencies

Research from the FER has been previously used to provide a scientific basis that supported development of policies related to effects of logging on stream sediment. Regulators might also use the extensive existing datasets and research results from FER to represent conditions and processes in headwater streams. For example, the long-term data from the FER reference watersheds might be used to represent conditions, including stream chemistry in relatively undisturbed headwaters in TMDL models.

Key points:

- The export of Ca and Mg have increased in response to elevated acidic deposition and the resulting stream acidification in FER watersheds. Sulfate is still being retained, but the rate of retention is declining.
- Stream acidity levels in some FER watersheds could negatively affect sensitive stream biota.
- Sediment inputs from land management activities remain a concern for stream water quality in the region.
- An important research need of water quality regulators related to stream SO_4^{2-}, Ca, and Mg is to understand the combined effects of acid deposition and land management activities on stream acidification and to develop models to predict the consequences of these interactions at the scale of larger watersheds and the region.

Overview and Synthesis

Long-term stream research on the FER provides high-quality data on streamflow and inorganic stream chemistry, with particularly rich datasets on stream water concentrations and fluxes of acidity, N, SO_4^{2-}, Ca, and Mg. Relatively little research has directly addressed the questions of biological responses to water quality on FER. However, data on some stream biota exist that could be used as baseline for comparative purposes; these data might be useful as indicators of biological communities that occur under conditions documented by long-term water quality monitoring data collected at FER. From the studies that have been done at FER, we know that streamflow and habitat characteristics are important influences on variability and distribution of aquatic biota, especially macroinvertebrates and brook trout. Among water quality parameters, only pH has been found to be limiting distribution of the aquatic biota that have been examined, although that relationship has not been rigorously studied on the FER. The lack of Al chemistry data is a deficiency that prevents a more mechanistic interpretation of pH and base cation effects.

Most of the water chemistry data collected on the FER comes from small headwater streams. Working at this scale has allowed experimental manipulations to evaluate effects of forest management activities, including harvesting and fertilization and some natural disturbances, such as floods on water quality and quantity. Regulators might use research results and monitoring data from the FER to represent effects of natural processes and forest management in forested headwaters in landscape-scale models to predict the influences of forests on the region's water quality.

Of interest to regulators, research at FER has found several indications that forested headwater basins in the central Appalachians have become larger sources of stream NO_3^- since the late 1970s, a trend that may continue into the future. A long-term watershed acidification study at FER found that experimentally tripling ambient atmospheric deposition raised stream NO_3^- to a concentration that approached the drinking water standard. Long-term observation of undisturbed, reference watersheds at FER also found that stream water NO_3^- has significantly increased since the mid-1980s despite minimal human disturbance and a measured downward trend in atmospheric deposition of N during the period. Taken together, these results imply that central Appalachian forested basins draining to the Chesapeake Bay are growing sources of NO_3^-, even as N deposition has declined, and might become even greater sources of NO_3^- if atmospheric deposition of N were to increase in the future. These findings are important for regional water quality regulatory agencies because, if NO_3^- from forested portions of the Chesapeake Bay continues to increase, controlling NO_3^- inputs to the bay might require more stringent regulation of urban or agricultural sources in its basin.

The highest priority research need, related to N, that could be addressed at FER, from the perspective of the regulatory community, would be to investigate whether stream NO_3^- exports from FER reference watersheds have responded to changes in atmospheric deposition of N as would be expected from results of the FER watershed acidification experiment. The highest priority research need, related to nutrients other than N or P, from the perspective of the regulatory community, would be to develop models to estimate combined effects of acidic deposition and land management activities on base cation depletion of soils and stream acidification.

Key points:

- FER has substantial long-term datasets and research results on physical and chemical conditions in headwater forested watersheds and streams.
- Relatively few studies have investigated biological communities in these streams, and those that did largely emphasized responses to physical habitat and stream pH. Instream variability was often greater than variability among streams in those studies.
- Extensive FER studies of effects of forest management activities on streams and long-term stream monitoring data from carefully maintained reference watersheds are potentially of immediate use to regulatory agencies for a number of practical purposes.
- Long-term monitoring of stream water NO_3^- and atmospheric deposition of N at FER suggest that increases in stream NO_3^- export from the region's forests have the potential to be an important issue for the region's water quality regulatory agencies.
- From the regulators' perspective, the highest priority research needs that could be filled at FER would be to reanalyze data to resolve any uncertainty in the findings that stream NO_3^- from the region's forests may be increasing in response to atmospheric deposition, and to develop models of the combined effects of acidic deposition and forest management activities on soil base cation depletion and stream acidification.

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