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Biological Responses to Stream Nutrients: A Synthesis of Science From Experimental Forests and Ranges



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Cover: Dungeness River, Olympic National Forest, photo by Alex Weinmann.

Biological Responses to Stream Nutrients: A Synthesis of Science From Experimental Forests and Ranges

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Abstract

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This report reviews existing research and datasets from 17 U.S. Forest Service-affiliated experimental forests and ranges (EFRs) that are relevant to science needs of state and federal water quality regulatory agencies. A focus group of regulatory personnel chose “biological responses to stream nutrients” as the focus for this synthesis, and identified a broader array of science topics that could be of regulatory interest. Additional research needs of regulators that could potentially be filled by future studies at these sites were identified as (1) the composition of biotic communities and responses to nutrient enrichment in low-nutrient reference streams, (2) effects on streams of forest management practices, and (3) aquatic impacts of air pollution and of climate change.

Monitoring of relatively undisturbed EFR reference watersheds provides data on baseline stream conditions useful for developing water quality criteria with the reference waterbody method. Studies at EFRs in eight ecoregions may provide a basis for nutrient stressor-response models, a second method for developing water quality criteria.

Management experiments at EFRs have been used to formulate and test best management practices for forests. Hypothesis-testing research into ecological mechanisms underlying stream processes at EFRs can be used to develop models of stream responses.

EFRs offer opportunities to expand research on classes of streams that are underrepresented in the regulatory science base, particularly headwater streams with detritus-based food webs and ephemeral and intermittent flows. Research networks containing multiple EFRs could be used to produce science needed to address large-scale regulatory issues that span multiple ecoregions. Cooperative research at EFRs involving water quality regulatory agencies and land management agencies could potentially produce mutual benefits.

Keywords: Reference watersheds, headwaters, water quality criteria, biological indicators, best management practices, research networks, total maximum daily load.

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Chapter 1: Experimental Forests and Ranges and Their Significance to This Synthesis

Douglas F. Ryan¹

Introduction

Experimental forests and ranges (EFRs) are a network of long-term, dedicated research sites that have been established nationwide by the U.S. Department of Agriculture, Forest Service (USFS), and include several collaborating research sites managed by other federal and state land management agencies (Adams et al. 2008, Lugo et al. 2006). Most were originally established to investigate the environmental effects of forest management practices, but, over time, many have become venues for long-term environmental monitoring and for investigations of fundamental ecological processes in these forests and the streams that drain them. Both federal and state water quality regulatory agencies potentially could use the research results produced at EFRs to provide a scientific basis for setting and enforcing regulations to protect the quality of the nation's water resources.

Although some state regulatory agencies have drawn upon EFR research results, this scientific resource has not been systematically used by the regulatory community despite its widespread recognition as a reliable source of relevant, peer-reviewed, scientific findings by the research and land management communities. This synthesis is a step toward facilitating use of science from EFRs by water quality regulatory agencies by informing them of existing research and monitoring that have been done at EFRs and by identifying what future investigations at EFRs could fill important regulatory science needs. The focus of this report is a question that is nationally important to water quality regulatory agencies: What are biological responses to stream nutrients?

Origins of This Synthesis

Beginning in 2011, the USFS and a partner, the National Council for Air and Stream Improvement, Inc., engaged personnel from state and federal water quality regulatory agencies to discuss how science and monitoring from EFRs could be made more useful to regulatory agencies. One suggestion endorsed by the majority of the regulatory participants was a synthesis of scientific results from EFRs that are relevant to regulatory issues. The group also identified the question of national regulatory interest that is the focus for this synthesis.

Followup with regulators has revealed that regulators' interests in EFR science were broader than just the focus question. Regulatory science needs included a wide

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variety of scientific topics studied at EFRs, many of which were only peripherally related to the focus question. For example, although all of the regulators queried were interested in effects of nitrogen and phosphorus, some wanted to learn about research on other nutrients as well. Regulators were also interested in physical factors that affect biological responses to stream nutrients such as flow, light, temperature, and suspended sediment. They wanted more information on integrated indicators of biological responses such as stream biomass, respiration, and chlorophyll, and chemical indicators such as stream dissolved oxygen and pH. Their interest included all kinds of biological responses, regardless of whether their effects were desirable, undesirable, or neutral from a human perspective. They wanted information about responses at all levels of biological organization, ranging from individual species and guilds to whole ecosystems and effects at multiple geographic scales, including reaches, basins, and regions. They also asked for data documenting land management treatment effects on streams, as well as effects of regional- and global-scale stressors, such as atmospheric deposition and climate change, regardless of whether these effects were directly related to stream nutrients. To embrace the regulators' wide range of interests, we asked authors of synthesis chapters on individual EFRs to address both the focus question and the science on these broader research areas of regulatory interest at their EFR.

Following another regulators' suggestion, we sought coauthors from the water quality regulatory community to contribute to each chapter. Their role was to comment on how the existing research and monitoring findings from individual EFRs could be used for practical purposes by the regulatory community and to help identify what gaps in the existing science at each EFR, if filled, would most benefit regulatory agencies.

Importance of the Focus Question

The Clean Water Act of 1977 (CWA) (United States Code 33, sections 1251–1387) established shared responsibility between federal and state governments for attaining the congressionally mandated, national goal to “restore and maintain the chemical, physical, and biological integrity of the Nation’s waters.” States were given the authority to set water quality standards within their boundaries to protect societal values based on what beneficial uses people make of waterbodies. The U.S. Environmental Protection Agency (EPA) was tasked with overseeing states’ actions to protect waters under the CWA and was given authority to set standards if a state declined to act on that responsibility.

Effects of water quality on aquatic biological communities have been a major concern of regulatory agencies for more than 20 years. The National Water Quality Inventory Report to Congress (USEPA 1996) stated that nitrogen and phosphorus

concentrations were one of the main causes of water quality impairment in the United States, with 40 percent of the rivers impaired from nutrient loads. The CWA specifically established as a goal the protection and propagation of fish, shellfish, and wildlife. The EPA has interpreted this protection broadly to include the aquatic community and not just fish, shellfish, and wildlife, giving states authority to set water quality goals to protect aquatic-life uses more generally. This can include, for example, sustaining healthy aquatic ecosystems needed by threatened or endangered species. To exercise this authority, state regulatory agencies draw upon research and monitoring from a wide variety of sources to provide a scientific basis for considering how aquatic ecosystems respond to stressors, including stream nutrients.

Protecting streams from the impacts of nutrient pollution has posed vexing issues for regulatory agencies. Nutrients in stream water originate from both well-defined point sources, such as sewer and industrial outfalls, and from more diffuse, nonpoint sources such as land use activities, and landscape-scale biogeochemical processes that may be difficult to identify and quantify. The EFRs reviewed in this report have mainly studied nutrients from nonpoint sources on forest lands. In syntheses that drew together studies done nationwide, Ice and Binkley (2003) and Binkley et al. (2004) found that nutrients in forest streams were influenced by the types of vegetation and underlying geologic composition in a watershed, atmospheric deposition, and natural- and human-caused disturbances, including floods, wildland fires, and land uses, such as timber harvests.

The responses of biological communities to nutrients in streams are complex. Nutrients are basic building blocks of life that are required by all organisms to survive and grow, so it is logical that low levels of nutrients may limit stream biological activity that society values such as the abundance of fish. However, paradoxically, valued services may also be compromised where nutrient levels are excessive. For example, eutrophication, which is the overstimulation of algal growth by an abundance of nutrients, can reduce dissolved oxygen, stressing desirable fish, and posing risks to public health by degrading drinking water sources.

In addition, biological responses to stream nutrients are often influenced by multiple environmental factors such as the timing and volume of waterflows, light levels, turbidity, the quantity of instream large wood, and water temperature. Furthermore, stream nutrient levels and biological responses to them may change over time as a result of environmental change, for example, natural disturbances, climate change, or shifts in land management. In short, understanding biological responses to nutrients requires a grasp of the complex interactions that produce the structure and function of aquatic ecosystems and ultimately sustain the beneficial uses of water bodies that society desires.

The EPA developed a strategy to address aquatic nutrients (USEPA 1998) and recommended that states develop numeric nutrient criteria that can be quantified and updated to stay abreast of evolving science. Examples of evolving science include improved understanding of local variations in water chemistry and biological community responses. Nutrient criteria that are biologically based are particularly desirable because they can be directly related to aquatic life designated uses; can be specific to waterbody types, such as streams; and can potentially integrate multiple stresses over space and time.

EPA technical guidance to states includes two approaches for developing numeric nutrient criteria: one based on reference waterbodies and another based on empirically derived stressor-response models. A reference waterbody approach (USEPA 2000) uses water quality conditions in relatively undisturbed, reference waterbodies in ecoregions around the country as a baseline, against which conditions in more polluted waters can be compared. More recently, EPA also recommended empirically derived stressor-response models that are based on data from studies of how biological communities are altered by changes in stream nutrient concentrations (USEPA 2010).

Water quality standards (40 CFR 131) must specify three values: (1) a magnitude, for example, a nutrient concentration or load selected to protect a designated use, such as recreational fishing; (2) a duration, which is a time period during which exceedances are a concern, for example, a fishing season, and a frequency, which indicates how many times conditions may exceed the magnitude during the duration, for example, three times a season; and (3) numerical water quality criteria, which provide a scientific rationale for selecting the values set in standards.

Despite federal guidance, states still struggle to set nutrient criteria, in part, because of scientific uncertainties about responses of aquatic biological communities to nutrients and how human activities affect them. Natural variability in water quality within individual waterbodies, among different waterbodies, and over time, contributes to the uncertainty. Knowledge is often lacking for selecting appropriate magnitudes, for example, when there is no scientific consensus on how nutrient levels affect designated uses, such as desirable biological communities. Deciding the correct duration and frequency for standards may be difficult owing to limited understanding of the rate at which ecosystems respond to acute and chronic nutrient enrichment and how quickly they recover after such events. Adding complexity, co-occurring stressors, such as temperature or other pollutants, and colimiting factors, such as food web energy availability, can obscure or antagonize effects of nutrient stress, but these interactions are often little studied. The spatial and temporal distribution of nutrient sources and their effects on aquatic biological communities

are also often unknown, hampering decisions about where regulations should apply. Research at EFRs has often used experimental designs that yield scientifically credible results, which may reduce some of these uncertainties.

Studies needed for setting standards to protect water quality during forest management operations, for example, can be complex because these practices often simultaneously alter many factors that affect stream water quality, including stream nutrients, flow, temperature, light, and suspended sediments. Where research is inadequate for setting numeric standards for forest management activities, agencies sometimes use nonnumeric, narrative standards or guidelines as alternatives. Such narrative standards include regulatory and nonregulatory best management practices (BMPs) that state and federal agencies develop to reduce water quality impacts of forest practices such as timber harvest and fuels treatments. Studies at EFRs have been the basis for developing or testing forest management BMPs in several parts of the country.

With their long history of research and monitoring of reference streams; studies of biological responses to a variety of stresses, including nutrients; and carefully monitored forest management experiments, EFRs have the potential to provide regulatory agencies with research results relevant to two approaches recommended by the EPA for developing numeric nutrient criteria as well as narrative standards.

Relevance of Experimental Forests and Ranges

EFRs are study sites owned and administered by federal or state land management agencies and dedicated to long-term environmental research. Over the past century, the USFS and state land management agencies have established EFRs in major forest types nationwide (USDA FS 2018). Most were originally intended to investigate the effectiveness of forest and range land management practices. Over time, studies at many EFRs evolved to include broader environmental implications of management and more basic scientific questions, including long-term environmental monitoring and hypothesis-testing ecological research. As a result, EFRs are among some of the relatively rare places in North America where long-running investigations of both basic ecological processes and effects of active land management have been well monitored. Studies at these sites have observed long-term environmental trends, and most of the older sites have studies that have outlasted the careers of the scientists who initiated them. In the past decade, the USFS has organized more than 80 EFR study sites into the EFR Network to encourage cross-site studies and syntheses that address large-scale and long-term questions of regional or national importance.

This synthesis focuses on findings from 17 EFRs, chosen because they contain intensively studied and monitored headwater streams (fig. 1.1). Fourteen of the

reviewed EFRs are on federal land and administrated by the USFS, while three, Caspar Creek Experimental Watersheds in California (chapter 11), Olympic Experimental State Forest in Washington (chapter 12), and Hawai'i Experimental Tropical Forest in Hawai'i (chapter 18), are on state lands and are administered by state natural resource management agencies that collaborate on research with the USFS.

Studies at the reviewed EFRs include topics relevant to the synthesis focus, such as water quality and quantity and stream and riparian biological processes. Stream studies are an enduring theme at these EFR sites because the USFS and its partner state agencies have long recognized that clean water for multiple uses is an important ecosystem service that headwater forests and rangelands provide to society. Headwater streams studied in these EFRs include the smallest reaches in which water flows above ground in a discernable channel. Headwaters comprise the majority of stream channel length nationwide, but they are often underrepresented

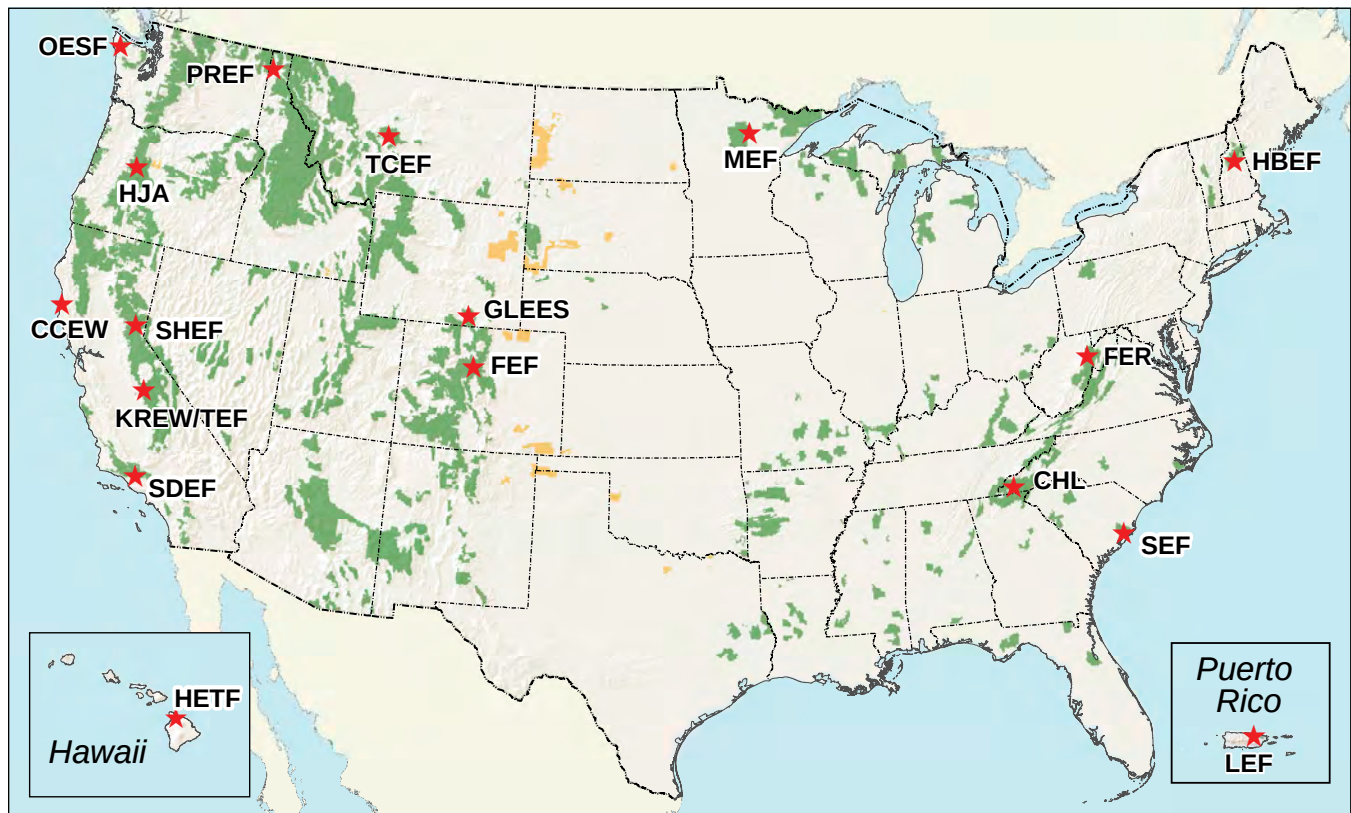


Figure 1.1—Experimental forest and range (EFR) sites with intensive stream studies that are reviewed in this synthesis. Key to EFR sites: MEF = Marcell Experimental Forest (EF), HBEF = Hubbard Brook EF, PREF = Priest River EF, HJA = H.J. Andrews EF, TCEF = Tenderfoot EF, KREW/TEF = Kings River Experimental Watersheds/Teakettle EF, SHEF = Sagehen EF, FEF = Fraser EF, GLEES = Glacier Lakes Ecosystem Experiments Site, OESF = Olympic Experimental State Forest, CCEW = Caspar Creek Experimental Watersheds, FER = Fernow EF, CHL = Coweeta Hydrologic Laboratory, SEF = Santee EF, SDEF = San Dimas EF, LEF = Luquillo EF, HETF = Hawai'i Experimental Tropical Forest.

on maps, because they are small and numerous. Leopold et al. (1964) conservatively estimated that first- and second-order streams contain 73 percent of total channel length in the United States, and more recently, Ice and Binkley (2004) estimated headwaters represent more than 90 percent of channel length. Where headwaters are in healthy condition, water quality is often high, but their water quality can be degraded by both human and natural causes. The long-running studies at these EFRs have investigated how a variety of stressors affect water quality and biological communities in headwater ecosystems in important forest-dominated ecoregions across the country.

Several aspects of EFR environmental research and monitoring make them potentially useful to water quality regulatory agencies. EFRs were deliberately located on sites with vegetation and topography that occur widely in their ecoregion, so their scientific results have strong potential to be broadly applicable. Public ownership and the relatively large area at most of the reviewed EFRs permit entire watersheds and their associated streams to be dedicated as study areas in which onsite human activities have been controlled or manipulated for research purposes. These basins can be studied over the long term, with control over confounding onsite land uses that might conflict with research, such as mining, agriculture, or urbanization. Environmental research at EFRs is place based, with multiple environmental factors monitored and studied within the same ecosystem at high temporal and spatial resolution. In addition, hypothesis testing experiments at EFRs investigate the mechanisms of ecological processes that are useful for developing models of ecosystem interactions that affect water quality. The intensive investigations at EFRs complement the more extensive stream monitoring often done by water quality regulatory agencies, which typically involve synoptic sampling of a limited number of parameters in a large number of geographically dispersed streams, for example, rapid bioassessment monitoring. Therefore, the ecological cause-and-effect relationships studied at EFRs may help explain spatial and temporal patterns observed in regional monitoring programs conducted by water quality regulatory agencies.

EFR streams are typically located in forest-dominated landscapes with histories of relatively low-intensity land use activities, such as forestry and grazing. Consequently, study streams at EFRs usually have relatively low nutrient concentrations compared to those in other areas in their ecoregions with more intensive urban or agricultural land uses. Investigations at EFRs can potentially provide insights into biological processes that occur in relatively undisturbed streams. Biological

responses to stream nutrients in these low-nutrient conditions could be useful to regulatory agencies for developing standards that protect streams with currently low loads from degradation.

Most EFRs in this synthesis have research mandates that permit imposing experimental manipulations on the landscape, including simulated or operational forest management practices, to study their long-term environmental effects. Results of these experiments have been useful for developing regulatory guidelines that protect water quality, such as BMPs, and for testing their effectiveness. One approach often used at EFRs has been paired watershed studies in which treated watersheds are compared with reference watersheds (watersheds where onsite human disturbances are minimized). Such studies have provided a basis for distinguishing effects of management treatments from effects attributable to natural variability.

The detailed studies of reference streams in carefully controlled EFR headwater basins also have an additional function. They serve as sites for indepth characterizations of ecological processes in relatively undisturbed streams and provide regulatory agencies with well-documented baseline data for developing water quality criteria. These data include scientific evidence of the range of natural variability, the composition of biotic communities, and long-term trends for stream nutrients in reference streams.

This document is focused on stream research at EFRs that are operated by the USFS or by state agencies that have formal affiliation with the USFS. Other experimental forest stream study sites, such as Hinkle and Alsea Creeks in Oregon, Mica Creek in Idaho, and Redwood Creek in California, have rigorous scientific studies of effects on streams of ecological processes and management practices that are of interest to water quality regulatory agencies, but were not covered here because those studies did not have formal ties with the USFS. For examples of forest and range stream studies at sites not covered in this report, see Ice and Stednick (2004) and NCASI (2012).

Audiences for This Synthesis

The primary audiences for this synthesis are government agencies that regulate water quality, including the EPA, and state agencies with analogous mandates, such as state environmental protection and natural resource agencies. A secondary audience for this report is the research community. This synthesis informs scientists about existing databases and research results from EFRs that are available for synthetic studies, and about what future studies at EFRs could be relevant to

science needs of water quality regulatory agencies. Other audiences of this report could include natural resource managers of both public and private lands interested in effects of forest and range management on water quality; educators and their students interested in research on stream ecosystems and its application to environmental policy; citizens groups who are concerned about regulatory decisions influencing natural resource management practices; and research managers, in agencies such as the USFS, who are interested in what future research may be of value to society and what collaborative relationships could potentially foster that work.

Organization of This Synthesis

Chapters on individual EFRs have been organized according to their Omernik ecoregions (Omernik and Griffith 2014; USEPA, n.d.), an ecological classification system commonly used by the regulatory community. For cross-reference, in table 1.1 we list these EFRs classified by their Omernik level III ecoregion, and the corresponding Bailey Ecosystem Province (Bailey 1995), an analogous ecological classification often used by the forestry community. Note that the EFRs in this report are located in ecoregions dominated by forest vegetation, because historically stream studies at EFRs were intentionally located in forests.

The main body of this report consists of chapters 2 through 18, which present the relevant science from individual EFR sites. Each of these site-specific chapters consists of a description of the EFR study site and its research history, a section that focuses on studies of nitrogen and phosphorus, and a section that focuses on studies of other nutrients. Each of these sections contains (1) a brief description of issues of concern for water quality related to these nutrients in forest streams of this ecoregion; (2) an overview of the relevant existing research results and monitoring data available at the individual EFR site; (3) identification of gaps in existing science at that site, which, if filled, would most benefit the regulatory community, and approaches to fill those gaps; and (4) a description of how existing data and science from that site could be used by the regulatory community. Each chapter ends with a synthesis of the work done at that individual EFR and its potential uses by regulatory agencies. Chapter 19 is an overall synthesis that takes a national perspective to summarize the science and monitoring data available from across the EFR network that could be used by the regulatory community. This chapter also identifies science gaps of interest to the regulatory community at multiregional or national scales that might be addressed using networks of EFR sites and suggests how these gaps could be filled.

Table 1.1—Experimental forests and ranges (EFRs) classified by Omerik Ecoregions (level III) and Bailey Ecosystem Provinces

EFR site	State	Omerik Ecoregion (Level III)^a	Bailey Ecosystem Province^b
Marcell EF	MN	5.2.1 Northern Lakes and Forests	212 Laurentian Mixed Forest
Hubbard Brook EF	NH	5.3.1 Northern Appalachian and Atlantic Maritime Highlands	M212 Adirondack-New England Mixed Forest-Coniferous Forest-Alpine Meadow
Priest River EF	ID	6.2.3 Columbia Mountains/Northern Rockies	M333 Northern Rocky Mountain Forest-Steppe-Coniferous Forest-Alpine Meadow
HJ Andrews EF	OR	6.2.7 Cascades	M242 Cascade Mixed Forest-Coniferous Forest-Alpine Meadow
Tenderfoot Creek EF	MT	6.2.10 Middle Rockies	M333 Northern Rocky Mountain Forest-Steppe-Coniferous Forest-Alpine Meadow
KREW/Teakettle EF	CA	6.2.12 Sierra Nevada	M261 Sierran Steppe-Mixed Forest-Coniferous Forest-Alpine Meadow
Sagehen EF	CA	6.2.12 Sierra Nevada	M261 Sierran Steppe-Mixed Forest-Coniferous Forest-Alpine Meadow
Fraser EF	CO	6.2.14 Southern Rockies	M331 Southern Rocky Mountain Steppe-Open Woodland-Coniferous Forest-Alpine Meadow
GLEES	WY	6.2.14 Southern Rockies	M331 Southern Rocky Mountain Steppe-Open Woodland-Coniferous Forest-Alpine Meadow
Olympic ESF	WA	7.1.8 Coast Range	M242 Cascade Mixed Forest-Coniferous Forest-Alpine Meadow
Caspar Creek EW	CA	7.1.8 Coast Range	263 California Coastal Steppe, Mixed Forest, and Redwood Forest
Fernow EF	WV	8.4.3 Western Allegheny Plateau	M221 Central Appalachian Broadleaf Forest-Coniferous Forest-Meadow
Coweeta HL	NC	8.4.4 Blue Ridge	M221 Central Appalachian Broadleaf Forest-Coniferous Forest-Meadow
Santee EF	SC	8.5.3 Southern Coastal Plain	232 Outer Coastal Plain Mixed Forest
San Dimas EF	CA	11.1.1 California Coastal Sage, Chaparral, and Oak Woodlands	M262 California Coastal Range Open Woodland-Shrub-Coniferous Forest-Meadow
Hawai'i ETF	HI	Not classified	M423 Hawai'ian Islands
Luquillo EF	PR	Not classified	M411 Puerto Rico

KREW = Kings River Experimental Watersheds, ESF = Experimental State Forest, GLEES = Glacier Lakes Ecosystem Experiments Site, EF = Experimental Forest, ETF = Experimental Tropical Forest.

HL = Hydrologic Laboratory, EW = Experimental Watersheds.

^a USEPA (n.d.).

^b Bailey (1995).

How to Use This Synthesis

This synthesis can be used to find research results pertaining to individual as well as multiple regions. To find research results that pertain to a particular state or ecoregion, go to the chapter that synthesizes the science and monitoring that has been conducted at an EFR site in the Omernik level III ecoregion in the state or ecoregion of interest. If there is no EFR site in that level III ecoregion, you may find useful science from EFR sites within the larger Omernik level II ecoregion that contains a particular location or in ecoregions that border on the relevant ecoregion (see table 1.1). If, on the other hand, you are interested in patterns or trends across multiple ecoregions, for example, from across several states or at the national scale, you may wish to review study results and data from multiple EFR sites. Most chapters on individual EFR sites have examples of previous synthetic investigations that have drawn from data from multiple EFRs and sometimes non-EFR sites that may serve as examples of cross-site studies. If you wish to go into more depth than is provided in this report, see the studies that are cited in individual chapters, or go online to published bibliographies for individual EFR sites to find additional research from studies at these locations. You may also be able to obtain observational data and metadata from EFR site electronic archives or by contacting scientists who conducted the studies.

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Chapter 2: Ecoregion 5.2.1 Northern Lakes and Forests: Marcell Experimental Forest, Minnesota

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Introduction

The Marcell Experimental Forest (MEF) has a rich and long history of research focused on peatland hydrology and biogeochemistry (Kolka et al. 2011c). Research at MEF has encompassed atmospheric deposition chemistry, peatland nutrient cycling, mercury (Hg) cycling, soil properties, tree-stand dynamics, and climate change. Various watershed treatments have been applied to uplands, bogs, or fens to investigate impacts of management practices on water yield, peak streamflow, water quality, and nutrient processing (Kolka et al. 2011b, Verry et al. 2011a). Biogeochemical research at MEF has focused on nitrogen (N), phosphorus (P), dissolved organic carbon (DOC), Hg, and sulfur (S) cycling (Urban et al. 2011). This chapter reviews monitoring and research that has occurred at the MEF related to nutrient biogeochemistry and biological responses to nutrients.

Site Description

The MEF is located in north central Minnesota (lat. 47° 31' 52" N, long. 93° 28' 07" W) (Verry and Janssens 2011). Elevations in the 1141-ha site range from 412 to 440 m. MEF straddles a continental divide and contains headwaters of rivers draining south to the Gulf of Mexico, and north to James Bay. MEF is the only site in the experimental forest and range (EFR) network of the U.S. Department of Agriculture, Forest Service (USFS) that focuses on the hydrology and biogeochemistry of naturally occurring peatlands in boreal forests (Sebestyen et al. 2011a).

The climate at MEF is continental, with moist warm summers and dry cold winters (Sebestyen et al. 2011a, Verry and Janssens 2011). The mean annual temperature is 3.4 °C (Sebestyen et al. 2011a). Monthly average temperatures range between 19 °C during July and -15 °C during January. Since 1961, the mean annual air temperature has risen by 0.4 °C per decade with the greatest increase in temperature occurring during the winter months (Sebestyen et al. 2011a). Annual precipitation averages 78 cm, of which 33 percent occurs as snow. Mean monthly

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precipitation ranges from 2.1 cm in February to 8.9 cm in August. Total annual precipitation has not changed significantly since 1961 (Sebestyen et al. 2011a).

Landforms of the MEF are a result of past glaciation (Sebestyen et al. 2011a). Lakes and peatlands formed from ice-block depressions that filled with organic soils of 3 to 10 m depth (Verry and Jannssens 2011). MEF contains forested bogs, fens, and poor fens developed on various types of peat. Bedrock geology consists of Ely greenstone and Canadian Shield granite overlain by 8 m of till and sandy outwash (Paulson 1968). Sandy loam soils comprise most of the uplands at MEF with sandy outwash soils also common.

Hydrology at MEF is influenced by glacial deposits that form a large regional aquifer. Bogs at MEF are perched above the aquifer and are fed by precipitation (Bay 1968, 1969; Verry and Boelter 1975; Verry et al. 2011c). The centers of most bogs are raised slightly and are surrounded by wet lagg zones (Sebestyen et al. 2011a). Water from the uplands and bog centers flow into the lagg zones, which drain from the bog through short (30 to 200 m) outlet streams. Although lagg zones are small in area, they are very important hydrologically in bogs (Verry et al. 2011c). Most outlet streams draining the bogs are intermittent, flowing only for a few months after snowmelt or during high precipitation periods. Flows from fens are less variable than those from bogs (Verry et al. 2011c). In fens, outlet streams are perennial, as a result of inputs from precipitation and groundwater from the aquifer. All of the outlet streams are low gradient (<0.5 percent), shallow, shaded, and with peat and silt substrate on the stream bottom.

Vegetation in forested uplands consists of mixed stands of white spruce (*Picea glauca* (Moench) Voss), trembling aspen (*Populus tremuloides* Michx.), bigtooth aspen (*P. grandidentata* Michx.), white birch (*Betula papyrifera* Marshall), balsam fir (*Abies balsamea* (L.) Mill.), red pine (*Pinus resinosa* Aiton), and jack pine (*P. banksiana* Lamb.) (Perala and Verry 2011, Verry 1969). Forested bogs contain the tree species black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.), eastern tamarack (*Larix laricina* (Du Roi) K. Koch), and northern white cedar (*Thuja occidentalis* L.) as well as various species of sphagnum mosses (*Sphagnum* spp.) and ericaceous shrubs (Sebestyen et al. 2011a). Speckled alder (*Alnus incana* (L.) Moench.) often is found in the lagg zone of these bogs. Open fens also contain speckled alder and a variety of understory species, including sedges (*Carex* spp.), marsh marigold (*Caltha palustris* L.), and cattails (*Typha* spp.).

Research History

Forests in the MEF region were logged between 1865 and 1897, prior to the establishment of MEF (Perala and Verry 2011). The area burned during widespread fires

in 1917, leaving the land unsuitable for agriculture and other uses (Sommer 2008). The Civilian Conservation Corps replanted red pine in a large portion of the southern unit of the MEF area between 1934 and 1941 (Perala and Verry 2011). MEF was formally established in 1962 as an experimental area of bogs, fens, moraines, and sandy drift, and it was divided into north and south units (Verry et al. 2011a). The site has six gaged watersheds, including two reference watersheds (S2 and S5) (fig. 2.1). The first streamflow gage was established at watershed S2 (Swamp 2) in 1960. Climate monitoring began in 1961, and water chemistry sampling began in 1966 (Verry et al. 2011a).

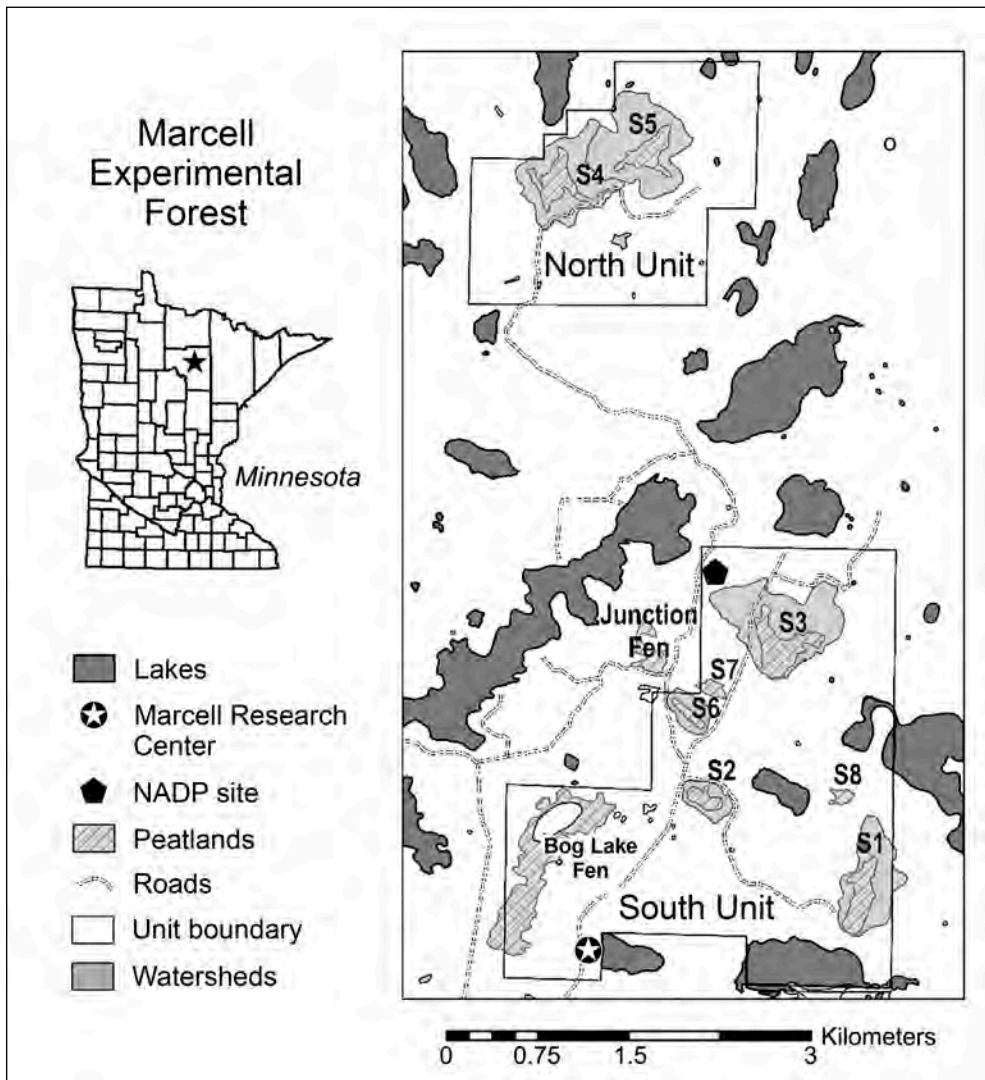


Figure 2.1—Watersheds in north and south units studied since 1961 at Marcell Experimental Forest (MEF), Minnesota. S1 through S8 designate the locations of the eight study watersheds at MEF. NADP = National Atmospheric Deposition Program. Map source: Marcell Experimental Forest, C. Dorrance, cartographer.

Past research—

Past research at MEF focused on both basic knowledge about hydrologic and biogeochemical characteristics of northern peatlands and applied studies related to forest management practices in peatlands. Watersheds at MEF were sites of the first detailed studies of water and solute budgets in bogs and fens in the Great Lake states (e.g., Bay 1967; Knighton and Stiegler 1981; Kolka et al. 2001; Nichols and Verry 2001; Urban 1983; Urban and Eisenreich 1988; Urban et al. 1987, 1989a, 1989b, 1995; Verry 1975; Verry and Urban 1992/1993). An analysis of long-term records of geology, soils, groundwater wells, water chemistry, peat-core dating, pollen analysis, and a review of glaciation records for the S2 reference watershed at MEF was used to interpret 12,000 years of ice-block peatland development (Verry and Janssens 2011). Peat from MEF watersheds was instrumental in research characterizing the physical properties of organic soils and their relationships to water (e.g., Boelter 1964, 1965, 1969; Nichols and Boelter 1984; Verry et al. 2011b). Diurnal and seasonal albedo variations and evaporation characteristics of various types of forested and harvested peatlands were documented at MEF by Berglund and Mace (1972, 1976) and Brooks et al. (2011).

Aquatic invertebrates were surveyed in April 2009 in outlet streams of watersheds S2, S3, and S6. A fish survey was conducted in April 2009 in the permanent outlet stream of S3. Data on periphyton standing crop as chlorophyll *a* and factors influencing benthic periphyton in streams were measured once from June to July 2012 in outlet streams of S1 through S6 and are presented below.

Watershed studies at MEF have evaluated hydrological and water chemistry responses to a variety of forest management techniques. Experimental manipulations have included upland clearcutting of aspen, N fertilization, soil compaction impacts, strip and clearcutting of black spruce, prescribed fire in a harvested fen, and conversion of upland aspen forest to conifer forests using cattle grazing and herbicides (e.g., Knighton and Stiegler 1981; Kolka et al. 2011b; Page-Dumroese et al. 2006; Perala and Verry 2011; Sebestyen and Verry 2011; Sebestyen et al. 2011b; Verry 1972, 1981). MEF was a pilot site for the North American Long-Term Soil Productivity (LTSP) experiment and one of four sites in the Great Lake states that demonstrated the effects of severe soil compaction and removal of organic matter on aspen productivity (e.g., Perala and Verry 2011, Powers et al. 2005). Results from these studies have been used to develop forestry best management practices for the Great Lake states (Verry 1975, 1976; Verry et al. 1983, 2000).

Current research—

Current research at the MEF focuses on hydrology, carbon (C), and Hg cycling, and climate change in northern peatlands. New hydrological studies have been initiated to investigate how rainfall interception, evapotranspiration, and subsurface flow differ between reference and managed watersheds and how climate variations affect tree growth (Kolka et al. 2011b). Long-term data collection continues on the rate of emissions of methane and carbon dioxide (CO₂) from bog and fen peatlands, the rates of carbon storage in peatlands, and variation in DOC composition among hydrologic flow paths (e.g., Grigal et al. 2011, Kolka et al. 2011b, Olson et al. 2013, Shurpali and Verma 1998, Shurpali et al. 1993). A large-scale, 10-year climate change experiment, named Spruce and Peatland Responses Under Climatic and Environmental Change (ORNL 2017), is underway in watershed S1. Responses of vegetation (above- and belowground), lichens, microbes, microinvertebrates, hydrology, and C, N, P, iron (Fe), methylmercury (MeHg), and S cycling to increased CO₂ concentrations and temperature are being monitored. Another recent study examined C, N, and P limitation and other environmental drivers on microbial processes and organic matter decomposition in a fen and bog at MEF (Hill et al. 2014, Seifert-Monson et al. 2014). Results from detailed studies of the inputs and fate of both total Hg and MeHg and interactions with S inputs in an 8-year, large-scale experiment continue to show the close relationship between sulfate (SO₄²⁻) and MeHg production in bogs (e.g., Coleman Wasik et al. 2012; Kolka et al. 1999a, 1999b, 2001; Mitchell et al. 2008a, 2008b, 2008c, 2009). In 2012, a study examining the effects of upland clearcutting and biomass harvesting on Hg cycling using enriched stable Hg isotope tracers was begun (Mazur et al. 2014). Results from each of these studies are critical for understanding mechanisms of biogeochemical cycling and predicting the consequences of global climate change and land management in peatland landscapes.

MEF also continues to participate in various long-term data networks. In 1978, MEF was established as one of the first National Atmospheric Deposition Program (NADP) (NADP 2017) sites in the United States. MEF was also a pilot site for measuring Hg deposition in the Mercury Deposition Network and developing methods for the LTSP Network. MEF also participates in the National Phenology Network, the EcoTrends Project Network, the United States-China Carbon Consortium, and the USFS EFR synthesis network (Kolka et al. 2011b). For more details about MEF and research conducted at MEF, see Kolka et al. (2011b, 2011c), Verry et al. (2011a), and USDA FS (2017a).

Availability of publications and data—

A partial bibliography of MEF scientific publications can be found online (USDA FS 2017d). A hydrology database is available (USDA FS 2017b). Metadata about the hydrology and climate database (air temperature, water tables, stream runoff, precipitation, soil properties, frost, and snow) are available online (USDA FS 2017c). Data from the Marcell NADP site (precipitation-weighted mean concentrations for calcium, magnesium, potassium, sodium, ammonium (NH_4^+), nitrate (NO_3^-), chloride and sulfate, pH, and conductivity) are also available online (NADP 2017). Long-term MEF daily streamflow and meteorological data, formatted for easy comparisons with a large number of other EFR and LTER sites, can be downloaded from the ClimDB/HydroDB website (LTER Network 2017).

Biological Responses to Stream Nutrients N and P

Issues of Concern

Nutrients such as N and P often limit the growth of benthic algae (periphyton) in streams and phytoplankton in lakes. Eutrophication results from excess dissolved N and P, which can stimulate algal production in headwaters such as those at MEF or in downstream waterbodies. The water standard for NO_3^- of 10 mg NO_3^- -N/L is based on the concentrations in drinking water that can cause methemoglobinemia in humans (Fan and Steinberg 1996). Multiple forms of N may also be toxic to aquatic life (Camargo et al. 2005). Biologically active forms of N, NH_4^+ , and NO_3^- , may be elevated in peatland streams by atmospheric deposition. Total nitrogen (TN) in wet deposition at MEF is similar to that reported from eastern forests (Aber et al. 2003, Driscoll et al. 2003). There has been no significant change in NH_4^+ in wet deposition at MEF since 1979, but NO_3^- concentrations in wet deposition have decreased over that same time period (Sebestyen et al. 2011a, Urban et al. 2011) corresponding with declines in regional emissions of N oxides (McDonald et al. 2010). Total phosphorus (TP) is of less concern than N in peatland streams as P leached from the canopy in throughfall and stemflow is strongly retained by soils, which are a net sink for P, and concentrations in peatland outlet streams are low (Urban et al. 2011, Verry 1975, Verry and Urban 1992/1993).

Findings From Studies**Nutrient levels in MEF peatland streams—**

Past research on N cycling in a MEF bog (S2) showed that high C:N ratios within bog peat (Malmer and Holm 1984, Urban and Eisenreich 1988) led to about 90 percent retention of inorganic N of inputs to S2 (Urban et al. 2011). Peak concentrations of NH_4^+ and NO_3^- in streamflow occur usually during early snowmelt, while

minimum concentrations occur in summer (Urban et al. 2011). Spring snowmelt is the only time of year when NO_3^- is measurable in the outflow from S2. Hill et al. (2014) reported NO_3^- concentrations at the outflow of a MEF bog was 0.711 mg/L (annual TN yield of 0.70 kg/ha/yr) and from a fen was 0.409 mg/L (annual TN yield of 0.73 kg/ha/yr), during May–October, from 2010 to 2012. Studies by Grigal (1991) at MEF found that perched bogs, which formed by lake filling, were less N limited than raised bogs, which formed by landscape swamping. Urban et al. (2011) projected that if the rate of atmospheric inputs of N continues its current decline of 1 percent per year at MEF, peatland watersheds would likely become even more retentive over time and experience decreases in terrestrial primary production, litter quality, and overall rates of N cycling.

Fewer data are available for P cycling in MEF watersheds. Urban et al. (2011) summarized data from Verry (1975) for total dissolved phosphorus solute concentrations in streamflow from a MEF perched bog (0.19 mg/L), groundwater fen (0.09 mg/L), and poor fen (0.47 mg/L) for the period 1968–1972. Hill et al. (2014) reported TP concentrations at the outflow of a MEF bog and fen of 0.301 mg/L (annual yield of 0.18 kg/ha/yr) and 0.032 mg/L (annual yield of 0.51 kg/ha/yr), respectively, during May–October from 2010 to 2012. Element budgets constructed for N and P suggest that 56 percent of N inputs and 38 percent of P inputs are retained in the S2 watershed on an annual basis (Urban and Eisenreich 1988, Urban et al. 2011).

Algal responses to stream nutrients—

Long-term studies of algal response to nutrients have not been done at MEF nor have such studies been done in other peatlands in the Great Lakes region, but a month-long study in 2012 suggested that nitrate may influence algal growth in MEF outlet streams. Periphyton standing crops in outlet streams were measured in June 2012 in the six MEF peatland watersheds with differing ambient stream water N and P concentrations to determine whether N and P, canopy cover, flow, water depth, water temperature, dissolved anions, dissolved cations, pH, and conductivity significantly influence periphyton growth. Tiles were placed in outlet streams and retrieved after 30 days for chlorophyll *a* analysis. Median periphyton standing crop during the June–July 2012 period in the six outlet streams ranged from 3.8 to 53.9 mg chlorophyll *a*/m² in the six MEF outlet streams (fig. 2.2). These results were below the benthic chlorophyll *a* values of >150 mg/m² in more than 1 year in 10 that the state of Minnesota considers to be excessive in Class 2B rivers and streams (Minnesota Administrative Rule 2018), but are similar to values measured in an Alaskan rich fen by another short-term study (Wyatt et al. 2012). Correlation analysis from the short-term monitoring showed that only NO_3^- was positively ($p = 0.03$) related to periphyton standing crops across all six watersheds (table 2.1). Total N

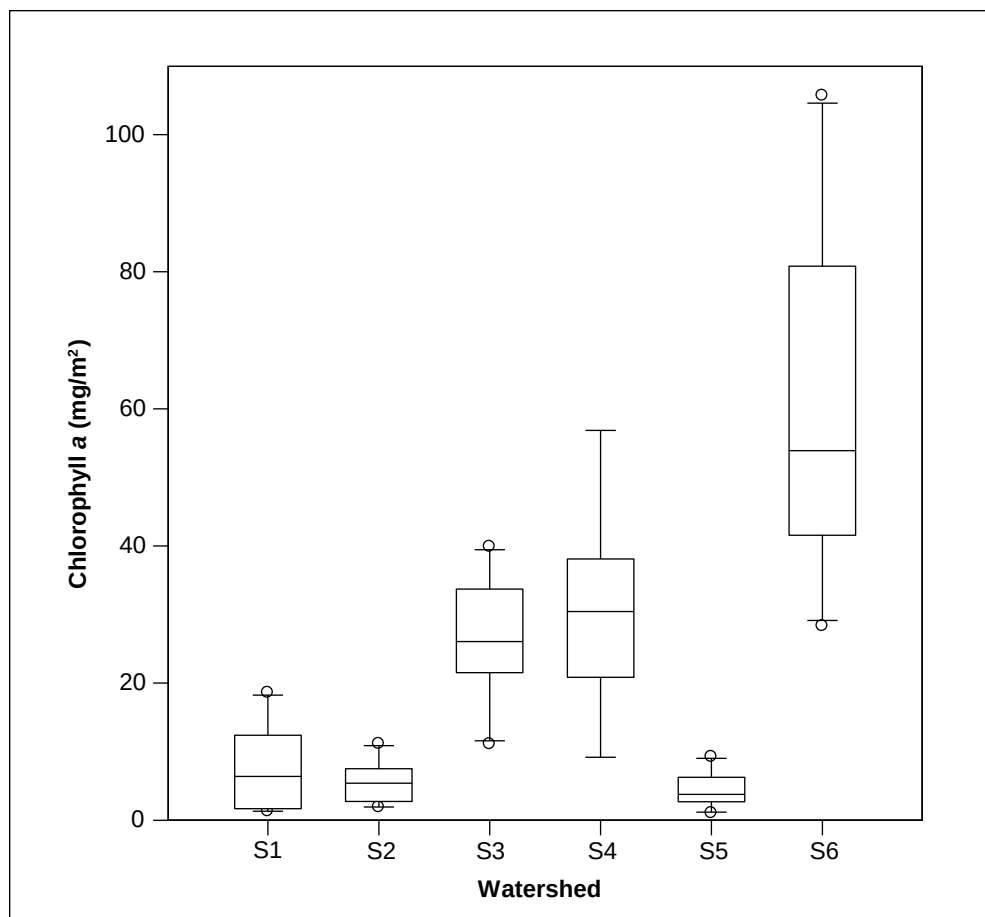


Figure 2.2—Median benthic chlorophyll *a* concentrations and 25th and 75th percentiles for six Marcell Experimental Forest outlet streams with a range of ambient nitrate concentrations (0.01 to 0.59 mg/L) in June 2012. Error bars = 10th and 90th percentiles. N = 10 tiles per watershed.

Table 2.1—Correlations among mean periphyton standing crops measured as chlorophyll *a* concentrations on tiles placed in stream bottoms, physical habitat variables, and water quality variables for six outlet streams (S1 through S6) with a range of ambient nitrate concentrations at Marcell Experimental Forest in June 2012^a

Factor	r	p	Factor	r	p
Percent canopy cover	-0.43	0.39	Nitrate	0.84	0.03*
Water depth	-0.46	0.36	Sulfate	-0.44	0.39
Current velocity	-0.10	0.86	Chloride	-0.68	0.14
pH	0.22	0.68	Calcium	0.15	0.78
Conductivity	0.02	0.98	Iron	0.13	0.81
Water temperature	0.68	0.14	Potassium	-0.70	0.12
Total nitrogen	0.75	0.09	Magnesium	0.22	0.68
Total phosphorus	0.19	0.72	Sodium	0.29	0.58
Dissolved organic carbon	-0.12	0.82	Silica	-0.29	0.58
Dissolved inorganic phosphorus	0.28	0.59			

^a Periphyton standing crop has significant relationship ($p < 0.05$) with factor of interest.

was positively but not significantly ($p = 0.09$) related to periphyton standing crops. No significant relationships between TP ($p = 0.72$) or dissolved inorganic phosphorus ($p = 0.59$) and periphyton standing crops were found. Multiple regression models relating chlorophyll *a* standing crop to important variables showed that only NO_3^- was a significant predictor of periphyton standing crops in peatland outlet streams ($\text{Chlorophyll } a \text{ [mg/m}^2\text{]} = 14.128 + [77.230 \times \text{NO}_3^-]$, $r^2 = 0.71$, $p = 0.03$).

Microbial responses to nutrients within peatlands—

Recent work by Hill et al. (2014) examined N, P, and C limitations on the microbial processes of respiration and coenzyme activity and organic matter processes within MEF fens and bogs. They found that microbial respiration, coenzyme activity, and decomposition were more closely related to soil pools of C, N, and P than to atmospheric sources of these elements, and suggested that localized nutrient availability may be a better predictor of peatland microbial processes in a changing climate than regional climate models.

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

Many other factors that may limit biological responses to stream N and P have been measured or monitored at MEF, including long-term streamflow, meteorology, atmospheric deposition, and DOC concentrations.

Short-term results from the periphyton colonization study described above suggested that none of the nonnutrient variables that were measured during the 30-day period, including canopy cover, flow, water depth, water temperature, and other water quality parameters of anions other than nitrate, cations, pH, DOC, and conductivity, were significantly related to periphyton standing crops in MEF outlet streams.

Dose-Response Studies

The only dose-response studies that have been conducted at MEF have been the short-term study of the response of periphyton to ambient stream nutrient levels described above.

Reference Watersheds

Two reference watersheds (S2 and S5) were established at MEF in 1960 and 1961, respectively (Sebestyen et al. 2011a). These watersheds are representative of relatively undisturbed bog watersheds in the region. Both watersheds contain second-growth upland forests that were previously logged in the late 1800s and have experienced multiple wildland fires since then, as have most watersheds in the region (Verry and Janssens 2011). Argerich et al. (2013) found no long-term

trends in nitrate or ammonium concentrations in stream water from these MEF reference watersheds, despite long-term declines in atmospheric deposition of N. This response differed from what has been found in mountainous reference watersheds in the Appalachians, where stream nitrate fluxes tracked long-term trends in atmospheric deposition of N (see chapters 3 and 14 on Hubbard Brook Experimental Forest and Coweeta Hydrologic Laboratory, respectively). No long-term trends in P in stream water from MEF reference watersheds have been reported.

The S2 reference watershed contains a 3.2-ha black spruce bog and a 6.5-ha aspen and birch upland (fig. 2.1) (Sebestyen et al. 2011a). The S2 watershed has been used as a reference for experiments conducted on the S1, S3, and S6 watersheds. The S5 watershed contains a 6.1-ha black spruce bog and a 46.5-ha upland of aspen and balsam fir (fig. 2.1). The S5 watershed is used as a control watershed for the S1 and S4 watersheds. Discharge from both reference watersheds is monitored with v-notch weirs at their outlets. Biweekly water chemistry samples have been collected upstream of the weirs since 1975 in S2 and S5, except for 1983–1988 when samples were not collected in S5. In watershed S2, chemical analyses have also been performed on samples collected during storms at the weir since 2008 and monthly water samples from a groundwater well in the upland since 1987 (Sebestyen et al. 2011a). Nutrient transport in surface runoff and interflow from S2 was reported by Timmons et al. (1977) and Verry and Timmons (1982) and is currently being monitored. Upland and bog wells have been monitored for water table elevations in both watersheds since the early 1960s. Meteorological stations in the uplands of S2 and S5 have recorded maximum and minimum air temperature, relative humidity, and precipitation in the watersheds since the early 1960s, and continuous air temperature has been measured since 1997. Snow and frost depth and snow water equivalents have also been measured in both watersheds since 1962. Peat and upland soil temperatures and upland soil moistures have also been measured in the reference watersheds at various intervals for varying periods of time. A complete list of hydrologic and climate variables measured in S2 and S5 over time is in Sebestyen et al. (2011a). Aquatic invertebrates were surveyed at the S2 outlet stream in April 2009 (Batzer et al. 2016) and periphyton standing crop as chlorophyll *a* and important habitat variables were measured in June–July 2012 in both S2 and S5 outlet streams.

Cross-Site and Regional Studies

MEF data on NO_3^- and NH_4^+ concentrations in forested peatlands were included in a synthesis study examining long-term trends in stream nitrogen concentrations for forest reference catchments across the United States (Argerich et al. 2013). A synthesis of streamflow responses to climate change by Jones et al. (2012) included

data collected at MEF. Impacts of forest management, such as harvesting and regeneration, on stream water yields at MEF were included in a cross-site comparison study of four experimental forests in the northeastern United States (Hornbeck et al. 1993). The S2 watershed served as an undisturbed reference site in a network of sites used to assess nutrient runoff over an agricultural gradient in Minnesota during the 1970s (Verry 2015). Long-term hydrology and climate data from MEF were included in a synthesis study examining interactions among climate, streamflow, and forest management practices at 10 U.S. USFS EFRs (Vose et al. 2012). The role that MEF played in the development of ecosystem science and biogeochemical cycling research at USFS EFRs was discussed in Vose et al. (2014).

Responses to Management

Effects of harvest and regeneration of upland aspen forests on stream chemistry—

To better understand the effects of aspen harvesting on water quality and stand regeneration, the uplands of the S4 fen were whole-tree clearcut during 1970 and 1971 (Perala and Verry 2011). After the seventh year of regeneration, the uplands were aerially fertilized with ammonium nitrate (340 kg/ha) (Bergusson and Perala 1988). Water yields and solute concentrations in one of two outlet streams of the harvested S4 watershed and the outlet stream of the S5 reference watershed were monitored from 1967 to 1982 and from 1989 to present (Sebestyen and Verry 2011). Water yields from S4 were elevated for 10 years after harvest (Sebestyen and Verry 2011, Sebestyen et al. 2011b, Verry 1972). NO_3^- + nitrite and NH_4^+ concentrations (annual volume weighted) and yield ratios (i.e., ratio of treatment to reference solute yields) did not increase in the treatment stream relative to the reference stream until the treatment watershed was fertilized in 1978 (Sebestyen and Verry 2011). Immediately after fertilization, the treatment to reference ratios of stream NO_3^- concentrations increased 97-fold compared to reference ratios, while treatment to reference ratios of ammonium concentration ratios increased 6-fold immediately after fertilization. Treatment ratios declined over 2 years but remained elevated over reference levels for 10 years. Biological responses to stream water N and P were not included in this study.

Conversion of an upland forest from hardwoods to conifers—

The uplands of the S6 bog were harvested by whole-tree clearcut in 1980 to test the efficiency of herbicide vs. cattle grazing in the preparation of hardwood sites for conversion to conifers (Perala and Verry 2011). Following harvesting, a portion of the S6 uplands was treated with the herbicide Weedone 170, while another portion was grazed by cattle (2.5 individuals/ha) for 3 years to prevent the regrowth of aspen. In

1983, the uplands were replanted with red pine and white spruce (Perala and Verry 2011). The S2 watershed served as a reference site for hydrologic and solute comparisons (Sebestyen and Verry 2011). While water yield increased immediately in S6 and remained high for 10 years (Sebestyen et al. 2011b), solute responses were delayed. Nitrate + nitrite concentrations and yield ratios increased by an order of magnitude during year 2 after clearcutting and declined immediately to levels observed in the S2 reference stream (Sebestyen and Verry 2011). Ammonium concentrations and yield ratios increased threefold during year 2 following clearcutting. Total organic N concentrations and yield ratios peaked during years 4 and 5 after harvest. Total P concentrations and yield ratios increased during the first 7 years after harvest (Sebestyen and Verry 2011). Fecal coliform counts were measured for 6 years to monitor the effects of cattle on stream water quality during the conversion from hardwoods to conifers (Sebestyen and Verry 2011). Fecal coliform counts were ~three times greater at the grazed S6 weir than at the reference S2 weir. Below the S6 weir, coliform counts were also higher in the outlet stream as a result of cattle entering the stream. Biological responses to stream water N and P were not measured in this study.

Response of phosphorus to clearcutting in a bog and fen—

Several experiments were conducted at MEF peatlands during the 1970s to examine harvesting effects on water yields and P concentrations in bog and fen watersheds (Sebestyen and Verry 2011). In the S1 bog, black spruce was whole-tree clearcut in alternating strips that left uncut trees to serve as seed source for regeneration in the cut strips (Verry and Elling 1978). Five years after regeneration began, the remaining uncut strips of black spruce were harvested. The S3 fen was clearcut harvested in the winter of 1972 and reseeded after burning (Sebestyen and Verry 2011). The hardwood uplands were not harvested during either experiment. Solute samples were collected from the pools of water backed up behind the weirs and not from the outlet streams. Results from the harvesting experiments were reported in Knighton and Stiegler (1981) and Sebestyen and Verry (2011). Water yields did not change in either the bog or fen after harvest (Sebestyen et al. 2011b). Total phosphorus concentrations above the weirs increased in both the fen and bog after clearcutting. The duration of the increase in total P in the fen lasted at least 6 years, after which data collection ended, while in the bog it lasted only 1 year. Biological responses to stream water phosphorus were not included in either of these studies.

Reliability and Limitations of Findings

No long-term research has been conducted on biological responses to nutrients in MEF outlet streams. One short-term study, described above, quantified periphyton accrual in MEF outlet streams with a range of nutrient concentrations. Although

this preliminary investigation suggests a positive relationship between NO_3^- concentrations in streamflow and algal biomass, it should not be considered definitive until measurements have been made for longer periods of time to account for seasonal and annual variability. Our knowledge of biological responses to nutrients in northern peatland streams is also limited by a lack of basic knowledge of the diversity, feeding habits, and life histories of organisms inhabiting the peatlands and baseline measurements of ecosystem functions such as primary and secondary production, respiration, nutrient spiraling lengths, and organic matter dynamics in peatland streams.

MEF hydrologic and biogeochemical research findings and datasets are likely to represent reliably upper Great Lake states forested bogs and fens that have relatively light human disturbance and low nutrient enrichment, and headwater streams fed by these peatlands. Outside of settings similar to these, MEF findings should be applied with caution and, where greater confidence is needed, validation studies should be performed to test how well MEF findings and data represent local conditions.

Research Needs

Research in the MEF has provided valuable insights into the effects of forestry practices on hydrology and nutrient export. Significant science gaps exist for both basic and applied questions regarding biological responses to N and P at multiple spatial and temporal scales. Of these science gaps, the basic information that would add the most to the existing body of MEF science related to biological responses to N and P would be how the structural and functional characteristics of microbial, algal, and invertebrate communities compare among MEF peatlands with differing natural levels of nutrients and how they vary seasonally and interannually.

Minnesota promulgated river eutrophication standards in August 2014, making some prior needs less pressing for regulators. However, long-term monitoring of ecosystem processes, such as primary and secondary production, nutrient spiraling, organic matter breakdown, and community responses of aquatic taxa, such as periphyton, invertebrates, and amphibians, that may be altered by nutrients and other management activities are needed by regulators for northern peatland streams. The concept of reference conditions is a high-priority science gap at MEF and should include not only water chemistry data but also aquatic invertebrate and aquatic plant data. These data are of considerable value for establishing “natural background” and are difficult to define where public and private lands may be co-mingled and collection of these data is the type of work that can only be done in an experimental forest setting. By more fully understanding natural processes, it is possible to establish natural background, which can be an issue in determining

whether a water quality impairment exists and can aid in total maximum daily load (TMDL) development.

To fill this highest priority gap, work is needed to address the following questions: Is periphyton growth controlled by ambient stream NO_3^- levels? Does this relationship hold across seasons and multiple years? Are microbial and invertebrate production driven by periphyton production or detrital resources? To address these questions, periphyton, invertebrate, and microbial production along with other selected environmental factors that might affect biological activity, for example stream nutrients, flow, temperature, light, leaf litter, DOC, pH, and conductivity, will need to be measured in six MEF streams for 10+ years. In situ monitoring devices that continuously measure factors such as dissolved oxygen concentrations and water temperature in outlet streams, may provide useful, high-resolution data. Collected data would be analyzed for evidence of specific factors that correlate with biological activity across the spectrum of MEF peatland streams.

Potential Utility to Water Quality Regulatory Agencies

It is important to understand how land use practices may contribute to excessive levels of periphyton and determine the relative importance of instream factors, such as habitat, light, and nutrients, on periphyton growth. Currently, data regarding biological responses to nutrients associated with land use practices do not exist for MEF streams. Results from future studies of stream responses to land use management at MEF may be useful for developing restoration strategies for total P-based TMDLs for low-order streams and serve as a basis for management of riparian corridors to avoid impairment, for example, from excessive periphyton growth or streambank erosion. Existing MEF datasets and analyses of N and P concentrations in stream water originating from forested peatlands could be used to represent contributions to streams from relatively undisturbed wetlands in TMDL models for this region. These existing data plus new collection efforts, as they become available, will augment the paucity of diel data we have on forested peatland streams and provide valuable biological data that can be used for future water quality standard refinements and Tiered Aquatic Life Use standards implementation.

Key points:

- At MEF, there is a long record of N and P monitoring in stream water draining several common peatland types in the northern Great Lake states.
- Responses of N and P concentrations in streamflow related to forest management activities at MEF generally have been of shorter duration and delayed when compared to results of management studies at other experimental forests.

- There have been preliminary, short-term studies regarding biological responses to ambient levels of nutrients N and P in MEF outlet streams under undisturbed conditions, but none in response to forest management experiments.
- The highest priority science gap at MEF related to N and P from the perspective of the regulatory community is to improve our understanding of natural biotic conditions in bogs and what the most important factors are in the growth and management of excessive levels of periphyton in outlet streams.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Sulfur is a macronutrient of concern in peatlands owing to its transport into peatlands via atmospheric deposition and its strong influence on the transformation of inorganic Hg to MeHg via microbial SO_4^{2-} reduction (Jeremiason et al. 2006, Kolka et al. 2011a). MeHg is of great concern because it bioaccumulates in aquatic food webs and reaches highest concentrations in apex predators, especially those that feed on fish. MeHg poses a risk to humans because it is a neurotoxin that people acquire by consuming MeHg-contaminated fish. Sulfate has been shown to penetrate down to the water table in the S2 bog where it is available to be reduced via dissimilatory SO_4^{2-} reduction (Urban and Bayley 1986). Sulfate concentrations in wet deposition at MEF have declined significantly since 1979, following the decline in sulfur dioxide emissions in the upper Midwest (Urban et al. 2011), but Hg deposition and MeHg in Great Lake states aquatic systems continue to be a regional concern (Evers et al. 2011). Apart from SO_4^{2-} and its effect on MeHg, there are no other major concerns in this region about biological responses to nutrients other than N and P.

Findings From Studies

Long-term monitoring—

There has been long-term monitoring of several nutrients other than N and P, including major cations, and anions, and DOC, in both stream water and atmospheric deposition at MEF (e.g., Urban et al. 1989a, 1995; Verry and Timmons 1982; Verry and Urban 1992/1993).

Sulfate levels in MEF peatland streams—

The cycling of S within peatlands is very similar to N cycling (Urban et al. 2011). Long-term records of SO_4^{2-} fluxes in streamflow from S2 and atmospheric deposition show that SO_4^{2-} is retained in MEF bogs (Urban et al. 2011). Peak concentrations of SO_4^{2-} in streamflow occur during early snowmelt, while minimum concentrations occur in summer (Urban et al. 2011). The decline in atmospheric inputs of SO_4^{2-} over time at MEF has not resulted in any significant declines in SO_4^{2-} export in streamflow (Urban et al. 2011). Element budgets constructed for S suggest that 42 percent of S is retained in the S2 watershed on an annual basis (Urban et al. 2011).

Interactions of S and Hg cycling in MEF peatlands—

Peatlands are sources of total mercury and MeHg to downstream lakes and rivers via export from outlet streams (Grigal et al. 2000; Kolka et al. 2001, 2011a). MeHg, the chemical species of mercury of greatest concern for human health, is produced in wetlands by biologically mediated processes that respond to the availability of the nutrient S in the form of SO_4^{2-} . In 2001, a large-scale experiment was initiated to investigate the effects of increased atmospheric SO_4^{2-} deposition on rates of methylation of Hg in peatlands (Jeremiason et al. 2006). Sulfate was delivered at four times the average 1990 deposition rate of SO_4^{2-} at MEF through a network of PVC pipelines and sprinklers encompassing the downstream half of the S6 bog for 5 years and compared to a control section located at the upstream half of the bog. Percentage of MeHg increased in porewaters of the treatment section of the bog immediately following SO_4^{2-} addition and remained elevated. MeHg increased over time in the peat, which served to retain newly formed MeHg (Coleman Wasik et al. 2012). Along with retention of MeHg by peat, MeHg yields in stream water also increased twofold (Jeremiason et al. 2006). Sulfate additions were discontinued in the upstream end of the treatment section after 5 years to create a recovery section. After ending the SO_4^{2-} addition, the percentage of MeHg declined in the porewater and peat in the recovery section relative to the treatment section over the 3-year recovery period, but remained higher than the control section (Coleman Wasik et al. 2012). Concentrations of total Hg in mosquito larvae collected in each experimental treatment paralleled MeHg levels in treatment sections, including the recovery section. This work suggested that SO_4^{2-} atmospheric deposition drove MeHg production and that lower regional SO_4^{2-} emissions and deposition could result in reduced MeHg contamination in aquatic food webs (Coleman Wasik et al. 2012). This relationship implies that past reductions in SO_4^{2-} emissions, which were primarily justified to reduce the acidity of precipitation, may have had an added benefit of

decreasing MeHg production in some aquatic systems. If the relationship between SO_4^{2-} deposition and MeHg production at MEF were found to be significant across wide geographic regions, it might provide an additional rationale for further reducing SO_4^{2-} emissions in the future.

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

Interactions among watershed topography, hydrology, and DOC in peatlands were also shown to be important predictors of MeHg production in the presence of SO_4^{2-} (Mitchell et al. 2009). A mesocosm study conducted in the SO_4^{2-} addition bog showed that added SO_4^{2-} resulted in decreased DOC concentrations (Seifert-Monson et al. 2014). Additional research in two bogs at MEF found MeHg hot spots within lagg zones that coincide with inputs of upland-derived SO_4^{2-} and DOC (Mitchell et al. 2008b). An experiment examining the effects of SO_4^{2-} and organic carbon on MeHg production demonstrated that the highest MeHg concentrations were reached only in the presence of both SO_4^{2-} and DOC (Mitchell et al. 2008a) at concentrations that were similar to those in the MeHg hot spots in the bog lagg zones at MEF (Mitchell et al. 2008b).

Reference Watersheds

Anions and cations, including SO_4^{2-} , have been measured at various times in outlet streams of reference watersheds S2 and S5 since the 1960s (e.g., Sebestyen and Verry 2011; Sebestyen et al. 2011a; Urban et al. 1989b, 1995, 2011; Verry and Timmons 1982). Chloride and SO_4^{2-} were measured during ice-free months 2010–2012 at an outlet of a bog and fen (Hill et al. 2014). Total mercury, MeHg, and DOC have been measured at various times in S2 and S5 from 1993 to 1995 and during 2005 (Kolka et al. 1999a, 2001; Mitchell et al. 2008c, 2009).

Cross-Site and Regional Studies

MEF participates in the National Trends Network, which produces maps of long-term records of precipitation chemistry, including SO_4^{2-} concentrations across the United States. MEF is part of a study examining litterfall Hg dry deposition in the Eastern United States (Risch et al. 2012). MEF has also participated in the Mercury Deposition Network (MDN) since 1996. The goal of MDN is to monitor regional Hg levels in precipitation. Total Hg concentrations in weekly precipitation are collected at the MEF NADP site and analyzed by Frontier Geosciences. Hg data from the MDN site were included in a study by Monson (2009), which reported a regional decline in Hg concentrations in fish in the 1980s and increases from the 1990s to 2006. The MEF NADP data are available online (NADP 2017).

Responses to Management and Natural Disturbance

Apart from the SO_4^{2-} addition experiment designed to simulate increased atmospheric deposition (Jeremiason et al. 2006), which was described earlier, effects of forest management and natural disturbance on nutrients other than N and P have not been studied at MEF.

Reliability and Limitations of Findings

The watershed-scale and long-term nature of the SO_4^{2-} addition to S6 was atypical of most studies done elsewhere and increased the reliability and applicability of the results. Biological responses to sulfate addition, such as microbial processes, and the potential bioaccumulation of MeHg in aquatic and terrestrial food webs, were not part of the original research plan. The limited mosquito larvae data that were collected after the SO_4^{2-} addition had ended demonstrated that measurements of more biological responses might have produced valuable information had they been originally included.

Research findings and datasets on SO_4^{2-} and Hg at MEF are likely to represent expected results in other acidic peatlands in the upper Great Lakes states. Outside of settings similar to MEF, however, results should be applied with caution and, where confidence is required, validation studies should be considered to test how well MEF results predict local responses.

Research Needs

The question that would add the most to the existing body of MEF science related to SO_4^{2-} and Hg is: How do various environmental factors influence MeHg availability to peatland biota? Filling this gap is of highest priority to regulators because watersheds differ in their efficiency at converting Hg to MeHg, and understanding what environmental factors influence this process might be useful for developing management strategies to control or reduce MeHg levels in biota. Filling this critical information gap at MEF would require continuing NADP SO_4^{2-} and Hg deposition monitoring and initiating long-term monitoring of major food web components, such as microbes, algae, detritus, aquatic invertebrates, and apex predators, including fish, amphibians, spiders, birds, and bats. Long-term monitoring of environmental factors, for example water temperature, SO_4^{2-} concentrations, atmospheric concentrations of CO_2 , and water table changes, to track the patterns of MeHg bioaccumulation in the food webs of peatland streams would also be required. The SPRUCE experiment at MEF, using enclosed mesocosms, also has the potential to contribute additional information about the cycling and mobilization of SO_4^{2-} , Hg, and MeHg in peatland soils and porewater subjected to warming and elevated CO_2 conditions and their effects on relatively immobile food web components such as microbes and macroinvertebrates.

Potential Utility to Water Quality Regulatory Agencies

Methylmercury continues to be a vexing problem. Insights into how MeHg forms and is processed within peatlands are of value for developing management strategies that could effectively reduce the amounts of Hg available for uptake in the food chain. Current total Hg and SO_4^{2-} deposition data being collected at the MEF NADP site will continue to be useful for monitoring and mapping regional Hg and SO_4^{2-} levels and trends in precipitation.

Key points:

- MEF research and monitoring have shown that SO_4^{2-} addition to peatlands results in increased MeHg production.
- There are hot spots of MeHg production, especially in lagg zones of peatlands related to upland runoff of solutes.
- Limited mosquito larvae data suggest that reducing SO_4^{2-} emissions might result in decreased MeHg accumulation in aquatic food webs, with potential reduction of risks to human health.
- The highest priority science gap at MEF related to SO_4^{2-} , from the perspective of the regulatory community, is the need for scientific information regarding the effects of atmospheric deposition of SO_4^{2-} and other environmental factors such as ambient temperature, atmospheric CO_2 , and changes in water tables on the bioaccumulation of MeHg in aquatic food webs of northern peatlands. The research and monitoring needed to fill this gap is continued monitoring of SO_4^{2-} and Hg deposition as well as further research on environmental factors that influence MeHg availability and bioaccumulation in peatland food webs.

Overview and Synthesis

Nutrient and hydrologic monitoring have been conducted systematically at multiple MEF watersheds for almost five decades. Seasonal and annual trends in N and P concentrations and hydrology have been documented in reference watersheds as well as nutrient concentration changes that occur as a result of atmospheric deposition, upland clearcutting of aspen, N fertilization, strip and clearcutting of black spruce, prescribed fire in a harvested fen, and the conversion of upland aspen forest to conifer forests. Detailed elemental budgets showed that most of the N and P inputs to MEF bogs and fens are retained, and seasonal variations in nutrient export are associated with snowmelt runoff. Changes in nutrient concentrations in response to land management activities at MEF are usually short lived but can differ between types of peatlands and type of disturbance. While there is a long history of chemical and

hydrological monitoring at MEF, there are no long-term biological data for establishing baseline or reference conditions, as well as understanding how forest management, atmospheric deposition, and other anthropogenic activities influence aquatic and riparian ecosystems. Recent short-term biological studies have suggested that NO_3^- concentrations may control algal growth in MEF outlet streams, and localized nutrient availability may be a better predictor of peatland microbial processes in a changing climate than regional climate models. However, biological processes in these peatlands have not been examined at larger spatial, or temporal scales.

MEF's long-term SO_4^{2-} concentrations in wet deposition have significantly declined, reflecting the decreases in sulfur dioxide emissions in the upper Midwest. Weekly measurements of total Hg levels in precipitation at MEF have also been critical in tracking declines in Hg deposition in the 1980s followed by increases in more recent years. An 8-year, watershed-scale addition of SO_4^{2-} at MEF, an experiment unique among EFRs, documented the close interactions between SO_4^{2-} and Hg cycles in northern peatlands. Although biological responses to SO_4^{2-} addition were not investigated thoroughly, results indicated that environmental SO_4^{2-} concentrations drove MeHg production and suggest that reduction in regional SO_4^{2-} emissions and deposition might potentially reduce MeHg bioaccumulation in aquatic food webs.

Despite the wealth of data collected at MEF, significant science gaps regarding biological responses to N, P, SO_4^{2-} , and Hg in northern peatlands remain. Science gaps of highest priority for the regulatory community include defining “natural background” or reference response of the biological community, including aquatic microbes, plants, and animals, to the range of ambient nutrient availability found in relatively undisturbed northern peatlands, and what environmental factors affect the cycling of N, P, SO_4^{2-} , Hg, and MeHg in northern peatland food webs. A better understanding of these relationships might be useful to regulatory agencies for developing standards for protecting water quality in northern peatlands. Information gaps of importance to regulators might be addressed by continuing long-term monitoring of chemical and physical environmental variables and by initiating new studies of biological responses at reference sites and sites that have undergone significant changes through anthropogenic impacts. Also, experiments such as the SO_4^{2-} addition experiment done at S6 and the current SPRUCE study can be extremely useful. Any studies done should consider biological as well as biogeochemical and hydrological responses. It could be of value for the USFS to convene a small group of state and federal scientists to design a program of research and monitoring at MEF that would address pressing science needs of mutual interest to water quality regulatory and land management agencies and propose actions for its implementation.

In the upper Great Lakes region, intact reference sites that provide systematic measurements of natural background conditions in streams and wetlands with minimal onsite human disturbance, are rare. The MEF affords water quality regulators with valuable long-term research results and monitoring datasets on chemistry and hydrology of reference streams for comparisons to similar, but humanly affected streams. This type of information along with results of future studies at MEF could benefit Minnesota regulatory agencies as they implement stream eutrophication standards and work toward applying Tiered Aquatic Life Use standards to streams of northern Minnesota.

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Chapter 3: Ecoregion 5.3.1 Northern Appalachian and Atlantic Maritime Highlands: Hubbard Brook Experimental Forest, New Hampshire

Robert O. Hall and Steve Fiske¹

Introduction

Element biogeochemistry in streams has a long record of study at Hubbard Brook Experimental Forest (HBEF) corresponding to the studies of watershed element cycling. Much of these studies focused on how streams control nutrient transport and storage. Although fewer HBEF studies have addressed how nutrients control stream processes than at some other experimental forests and ranges (EFRs) and long-term ecological research (LTER) sites (Benstead et al. 2009, Davis et al. 2010, Rosemond et al. 2015, Slavik et al. 2004), some studies at HBEF have addressed nutrient or cation enrichment (Hall et al. 2001b, Stelzer et al. 2003). This paper reviews element biogeochemistry studies at HBEF in relation to how nutrients affect biological properties of stream ecosystems.

Site Description

HBEF is in the White Mountain National Forest of New Hampshire (lat. 43.94° N, long. 71.75° W). Altitude ranges from 180 to 1000 m. Climate is cold continental with long cold winters and short cool summers. Monthly mean air temperature ranges from -9 °C in January to 18 °C in July. Hubbard Brook receives 1400 mm/yr of precipitation evenly distributed throughout the year and with about 30 percent as snow. Bedrock geology is a combination of metamorphic schist and igneous rocks. Average slope of the watershed is 21 percent but can be as high as 70 percent. Forest vegetation is northern hardwood with the principal tree species being sugar maple (*Acer saccharum* Marshall var. *schneckii* Rehder), yellow birch (*Betula alleghaniensis* Britt.), and American beech (*Fagus grandifolia* Ehrh.). Streams at HBEF range from first-order ephemeral streams to the fifth-order Hubbard Brook, which drains the entire valley (fig. 3.1). Drainage area of the south-facing experimental watersheds ranges from 12 to 42 ha. The smallest of these contain perennial first-order streams. Sediments are coarse, ranging from gravels to boulders, with a step-pool morphology and some dams created by large woody debris (Bilby 1981, Warren et al. 2007). Streams have slightly negative acid-neutralizing capacity, and pH can range from 4.5 to 6. For more details see Fahey (2017).

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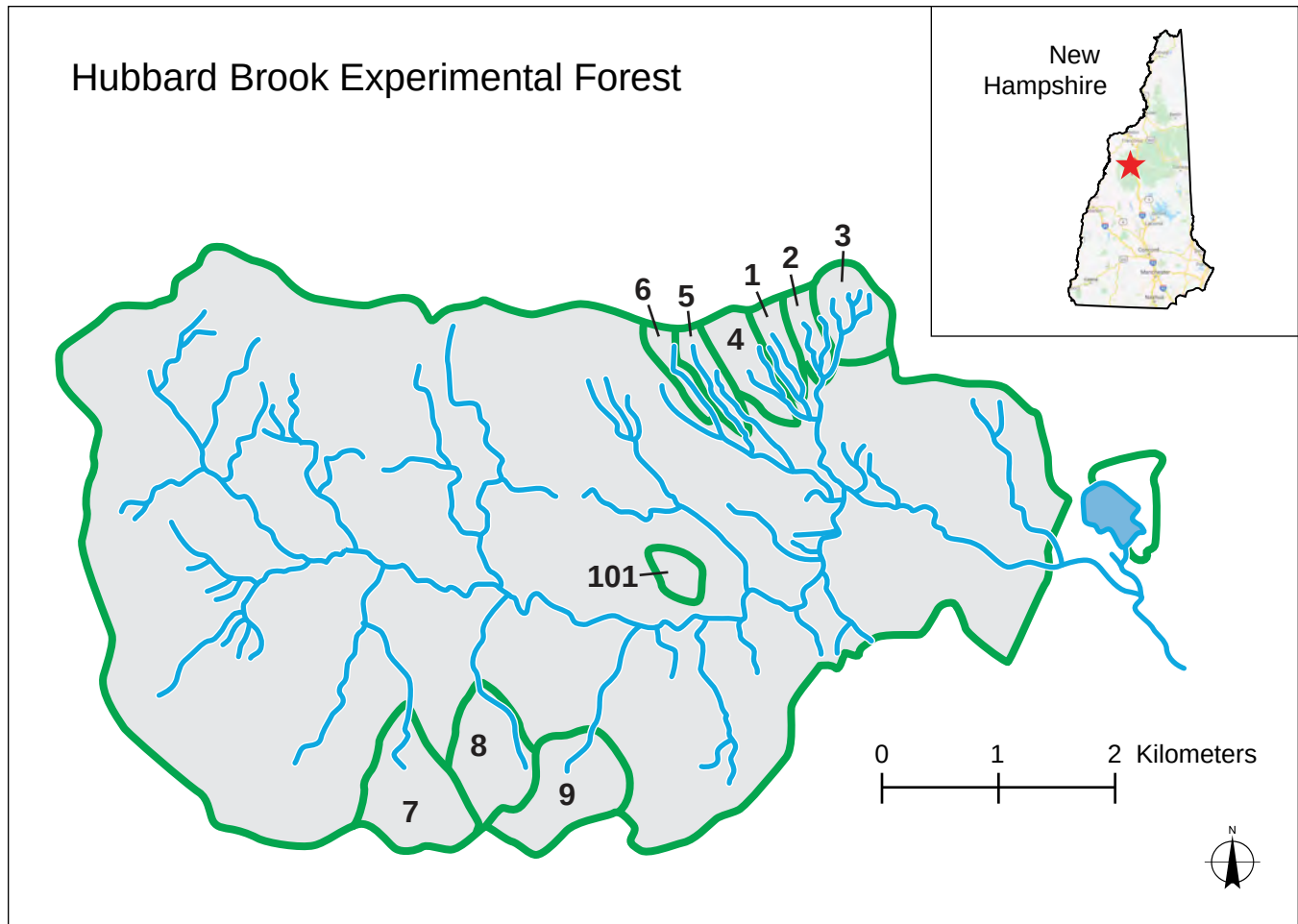


Figure 3.1—Hubbard Brook Experimental Forest. Numbers identify study watersheds.

Mirror Lake, within the Hubbard Brook drainage, has been the location of many integrated studies of lake ecosystem processes, including biological responses to aquatic nutrients (Likens et al. 1985, Winter and Likens 2009), but those studies of lake ecology are beyond the scope of this report.

Research History

Established by the U.S. Forest Service (USFS) in 1955, HBEF is notable for its long-term record of watershed biogeochemistry and experimentation. Since the early 1960s, it has been the site of an integrated ecosystem study that has investigated the large-scale and long-term ecological processes of this forest and its responses to experimental and management-oriented manipulations. Throughout its history, a central goal has been to maintain continuous monitoring of climate, streamflow, stream and precipitation chemistry, and numerous physical and biological components of aquatic and terrestrial ecosystems, such as forest vegetation, soils, and

animal populations. Many studies have focused on the small, gaged headwater catchments together with their associated streams and upland forests. The biogeochemical record for precipitation and stream water extends from summer 1963 to the present. These chemical data coupled with hydrological measurements allow long-term estimates of watershed nutrient budgets. In addition, there have been several whole-watershed experiments: three of these examined watershed response to forest cutting (Likens et al. 1970, Martin et al. 2000), and another examined watershed response to addition of calcium in the form of the mineral wollastonite (Cho et al. 2012). Reference watersheds, which have had minimal human disturbance, have been especially useful both for comparisons with experimentally manipulated and managed watersheds and to show long-term changes that are occurring in the absence of human impacts on land use. Since 1988, HBEF has been an active participant in the National Science Foundation's LTER Network, which is a consortium of site-based ecological studies that collaborate in cross-site studies and data-sharing networks (LTER Network 2017). Atmospheric deposition has been monitored at HBEF since 1978 as part of the National Atmospheric Deposition Program, or NADP (NADP 2019).

Availability of publications and data—

A bibliography of HBEF scientific publications is available from the Hubbard Brook Ecosystem Study website (HBES 2017). Numerous datasets with accompanying metadata from a wide variety of HBEF studies have been electronically archived and also are available at (HBES 2017). Site long-term daily meteorological and stream monitoring data, formatted to be readily compared with other EFR and LTER sites, are available at the ClimDB/HydroDB website (LTER Network 2013). Atmospheric deposition data are available from the NADP website (NADP 2019).

Biological Responses to Stream Nutrients N and P

Issues of Concern

Nitrogen (N) is an element of primary concern at HBEF because atmospheric deposition has been high. Rates of deposition average about 7 kg N/ha/yr and have declined only recently (Likens 2013). These high rates of deposition can alter watershed N cycling (Aber et al. 2003). For example, over large spatial scales, surface water nitrate (NO_3^-) concentration increases with increasing N deposition (Aber et al. 2003).

Phosphorus (P) enrichment is less of a concern than NO_3^- in forested mountain streams unless there are direct fertilizer or septic inputs. In wildland forest, there is little precipitation input of P (Yanai 1992), which, combined with sorption in the mineral soil, drive low levels of soluble reactive P and total P in streams (Meyer and Likens 1979).

Findings From Studies

Overall nutrient conditions—

Nitrate has been highly variable in stream water at HBEF and has ranged from $<10 \mu\text{g N/L}$ to $>5 \text{ mg N/L}$. In the 1960s and 1970s, NO_3^- was the dominant form of N. By the 1990s, dissolved organic nitrogen (DON) was the dominant form of N (Campbell et al. 2000). Stream NO_3^- concentrations show strong seasonal patterns; winter concentrations are higher than those during summer (Likens 2013). In addition, there has been a long-term trend toward lower NO_3^- concentrations in stream water at HBEF. Nitrate concentrations in recent years (2000–2012) were much lower than those in the first two decades of the record (Likens 2013), which is consistent with regional declines in stream NO_3^- (Goodale et al. 2003) (fig. 3.2). Controls on this decline are unclear, though one study suggests that the decline represents a long-term response to forest disturbance (Bernal et al. 2012). Newer work links the decline in NO_3^- to a decline in calcium (Ca^{2+}). Evidence supporting this connection is the observed delayed increase in NO_3^- export from watershed W1 following the experimental addition of wollastonite (CaSiO_4) to that watershed (Rosi-Marshall et al. 2016). Nitrate concentration in streams varies spatially; some watersheds (e.g., WS 4) have higher NO_3^- concentrations than others, possibly owing to variations in hydrologic flow paths and geology (Likens and Buso 2006). Over the entire Hubbard Brook valley, NO_3^- , ammonium (NH_4^+), and soluble reactive P (SRP) exhibit lower spatial autocovariance than that for other ions; the mechanism for this finding

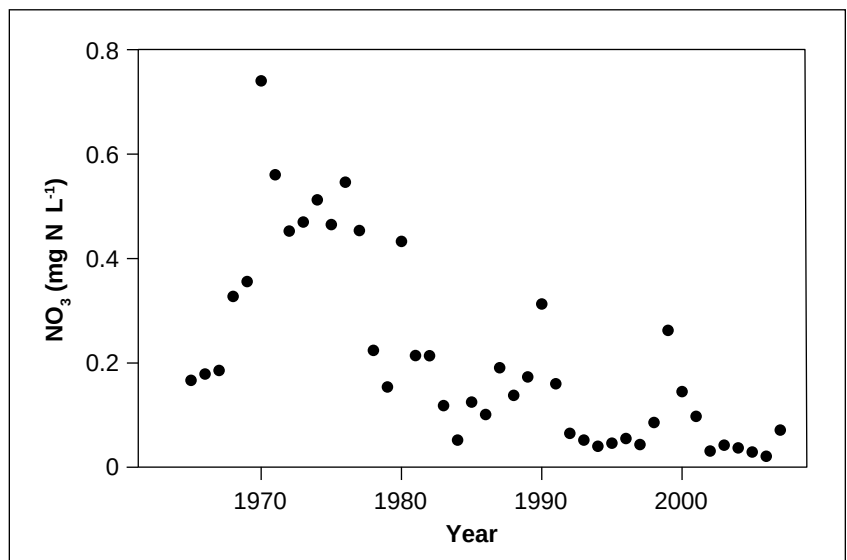


Figure 3.2—Time series of annual volume-weighted nitrate (NO_3^-) -N concentrations in stream water from a watershed at Hubbard Brook Experimental Forest shows strong variation through time with decline following 1980. Data source is from Likens (2012).

may be that stream uptake for these elements is so high that it breaks spatial structure in their concentrations (McGuire et al. 2014).

Because of high biological demand and rates of nitrification, NH_4^+ concentrations in streams are very low, typically $<5 \mu\text{g N/L}$ (Bernhardt et al. 2002, Hall et al. 2002).

Stream water P concentrations are very low. Dissolved P is $<10 \mu\text{g P/L}$. Particulate P is $<1 \mu\text{g P/L}$ at baseflow, but can increase to $100 \mu\text{g P/L}$ during storm flows (Meyer and Likens 1979). Most export of P occurs at highest flows following accrual of P associated with detrital organic matter (Meyer and Likens 1979).

Biological responses to stream nutrients—

There has been some research at HBEF examining the degree of nutrient limitation via N or P on biomass accrual of algal primary producers. Short-term bioassay experiments conducted in 1997 showed a strong, positive N effect on chlorophyll *a* accrual associated with benthic algae (Bernhardt and Likens 2004, Tank and Dodds 2003) (fig. 3.3). Subsequent experiments showed little effect of N or P, when added separately, on algal biofilm development in the forested streams of HBEF. A bioassay experiment in the main-stem Hubbard Brook showed that a large, positive impact of combined N and P addition on chlorophyll *a*

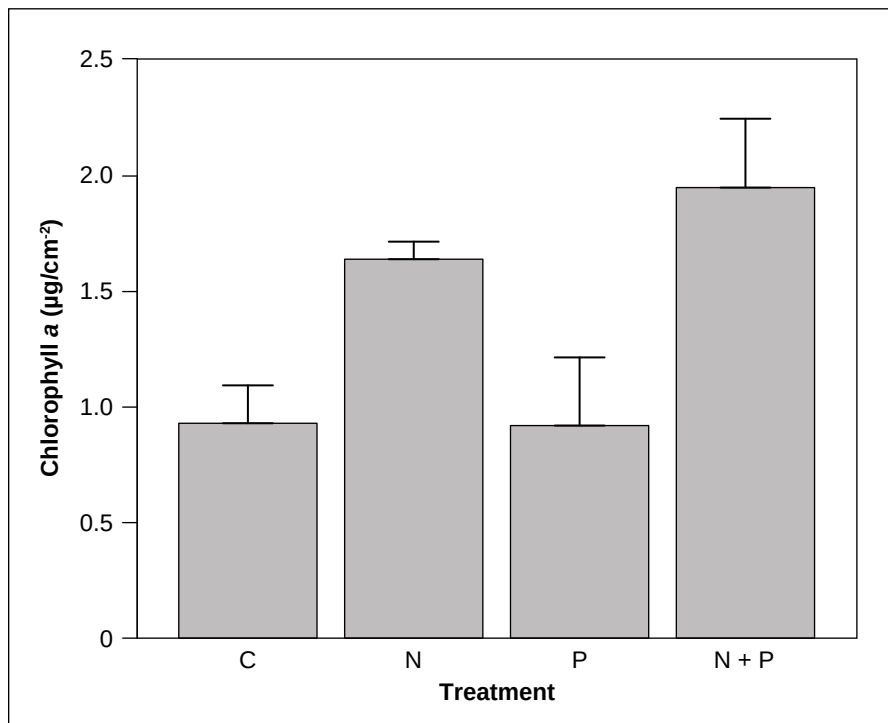


Figure 3.3—Response of bioassay experiment in Bear Brook shows strong response to nitrogen (N) alone in 1997. C = carbon, P = phosphorus. Data from Tank and Dodds (2003).

accrual can occur (Bernhardt and Likens 2004). This finding that Hubbard Brook streams are sometimes colimited by N and P is not surprising given that colimitation patterns are common in many oligotrophic streams (Johnson et al. 2009). Variation in ambient concentrations of N or P among streams has no apparent effect on stream algal assemblages at HBEF (Bernhardt and Likens 2004).

Only one whole-stream N+P addition at HBEF has been intended to alter biogeochemical cycling (Stelzer et al. 2003). This 9-week addition of N and N+P to Norris Brook was designed to measure nutrient controls on respiration and microbial productivity. Results showed the nutrient additions stimulated fungal production and organic matter respiration, but not bacteria (Stelzer et al. 2003). Response to N+P was stronger than N alone, suggesting secondary limitation by P; this finding agrees with nutrient bioassays showing colimitation by N and P on algal chlorophyll accrual (Bernhardt and Likens 2004).

No studies at HBEF have linked animal production, biomass, or assemblage structure to variation in stream nutrient concentrations. Experimental NO_3^- addition to Bear Brook Watershed in Maine has shown little effect on animal secondary production (Simon et al. 2010) because N is not a limiting nutrient in that stream. This finding suggests the response to N by higher trophic levels in HBEF streams is likely to be low or nonexistent because of equivocal findings on N limitation.

Control of nutrient dynamics by stream ecosystem processes—

Most studies of nutrients in streams at HBEF have investigated how streams alter nutrient concentrations by removal from the water column, and as a secondary question, how variation in concentration can affect nutrient removal.

Streams can strongly control cycling of NH_4^+ , NO_3^- , and dissolved P (measured as SRP). Experimental tracer additions show that streams remove these ions quickly from the water column (Hall et al. 2002, Meyer 1979, Webster et al. 2003). Controls on variation in nutrient uptake length are more difficult to identify. Increased transient storage of water only weakly increased nutrient demand and only during summer (Hall et al. 2002). Changes to the physical structure of streams (i.e., large wood) can increase dissolved P uptake in streams (Warren et al. 2007) and regulate particulate N export (Bilby 1981). Increased availability of labile carbon (C), from a whole stream acetate addition, lowered ambient NO_3^- concentration and increased nitrate demand at HBEF (Bernhardt and Likens 2002). Short-term leaf leachate addition in 2008 also lowered ambient NO_3^- concentration (Bernhardt and McDowell 2008). Variation in stream water nutrient concentrations may affect the degree to which streams process nutrients (Hall et al. 2009, Mulholland et al. 2008). At HBEF, assimilatory and dissimilatory demand for NH_4^+ is high, but declines with increasing nitrate concentrations (Bernhardt et al. 2002). Nitrate appears to control

the fraction of NH_4^+ that is nitrified, with more nitrification at higher NO_3^- concentrations, perhaps because of reduced competition for ammonium ions between heterotrophs and nitrifiers at high NO_3^- concentrations (Bernhardt et al. 2002).

Rates of NO_3^- demand relative to the concentration in stream water are so high at HBEF that it has led researchers to examine the role of instream processing on watershed NO_3^- export. An ice storm in 1998 damaged vegetation in a discrete elevation band of watershed 6 (Rhoads et al. 2002). This damage produced the typical increase in stream NO_3^- concentrations observed following vegetation removal (Likens et al. 1970), but this increase in NO_3^- declined downstream of the elevation band of ice damage, showing net removal of NO_3^- by the stream where it flowed through undamaged forest. This effect led investigators to explicitly consider the role of streams in nutrient output (Bernhardt et al. 2003, Hall 2003), including whether stream uptake may play any part in explaining long-term nutrient declines at HBEF. Although this question is unresolved, a modeling study suggests that changes in stream uptake cannot explain recent decline in N export at HBEF (Bernal et al. 2012).

Streams readily remove P from the water column, though much of this removal may be via sorption (Hall et al. 2002, Meyer 1979). Research by Meyer and Likens (1979) showed how hydrologic variation in Bear Brook regulated P concentrations and budgets. Streams regulated P export by storing P during periods of low flow and exporting P during large floods. Volume of wood was positively associated with P removal from the water column, suggesting that streams with large amounts of wood will have higher P retention and storage (Bilby 1981, Warren et al. 2007).

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

There have been several observational and experimental studies at HBEF examining how physical factors other than nutrient supply can alter stream biological assemblages. Light can limit algal production. Experimental shading in open-canopy headwater streams lowered algal biomass but had no effect on macroinvertebrate abundance (Fuller et al. 2004). The importance of terrestrial detritus for aquatic macroinvertebrates in HBEF streams stems from the finding that clearcut headwater stream reaches had lower macroinvertebrate abundance than forested reaches, likely because of lower food supply from terrestrial detritus (Fuller et al. 2004). This finding agrees with the observation of lower macroinvertebrate secondary production in the open-canopy, main-stem Hubbard Brook relative to the closed-canopy Bear Brook (Hall et al. 2001a).

Discharge variability is high at HBEF and may alter stream ecosystem function, yet little is known about this topic at HBEF (Hall and Likens 2000). There was

no effect of a flood with a cumulative annual probability of 1.52/yr on Bear Brook invertebrates or epilithon chlorophyll (Hall and Likens 2000), although this observation does not rule out the possibility that larger magnitude floods might affect stream biota.

Fish assemblages at HBEF are limited to small populations of brook trout (*Salvelinus fontinalis*). Acidification is the primary threat to fishes in mountain streams in the northeastern United States (Warren et al. 2008). Trout and sediment can reduce spring salamander (*Gyrinophilus porphyriticus*) abundances (Lowe and Bolger 2002) in New Hampshire streams, and newer evidence shows that climate variation controls long-term trends in salamander abundance (Lowe 2011). There is no known effect of nutrients on vertebrate assemblages in these streams.

Cross-Site and Regional Studies

Bear Brook at HBEF was one of the 11 sites in the cross-site Lotic Intersite Nitrogen Experiment 1 (LINX1) which compared the fate of isotope-labeled ^{15}N added as $^{15}\text{NH}_4^+$ to streams across the United States. Relative to other sites during the 1997 additions, Bear Brook had high rates of regeneration of labeled $^{15}\text{NH}_4^+$, showing rapid turnover and short uptake lengths because of low stream discharge (Peterson et al. 2001). However, this process was not detectable when it was remeasured in 2008 (Peterson et al. 2001).

Several cross-site synthesis efforts have used HBEF data to increase understanding of water quality variability and responses of water quality to watershed change across North America (OSU 2011). Topics of these water-quality syntheses include (1) trends in N concentrations in reference basins across the United States (Argerich et al. 2013); (2) addressing nutrient criteria using reference basin data (Rhoads et al. 2011); and (3) effects of forest disturbance on stream chemistry dynamics, concentrations, and fluxes (Johnson et al. 2008). HBEF also participated in a synthesis of long-term hydrologic responses to ecosystem processes, human influences, and climate change from sites across North America (Jones et al. 2012). This study showed an equivocal response of streamflow to climate change owing to possible local factors overriding the effect of climate change.

Responses to Management

Watershed response to forest harvest is well-studied at HBEF, with much research showing increased export of dissolved ions following harvest, and a rapid recovery with vegetative regrowth (Likens et al. 1970). There is evidence of algal blooms following harvest, but these could also have been a response to increased light.

Watershed (WS) 2 had large summer algal blooms following deforestation (Likens et al. 1970). Whole-tree harvest in WS 5 greatly increased epilithic algae, mostly owing to increased light availability (Ulrich et al. 1993), with a corresponding increase in primary production (Findlay et al. 1993). The same experiment altered bacterial populations via change in pH and organic C (Haack et al. 1988).

Less is known about how forest harvest affects aquatic invertebrates at HBEF or in similar New England streams. Despite an increase in algae, invertebrate density was lower in WS 5 following whole tree harvest (Fuller et al. 2004); this result differs from the increased abundances of algal-feeding mayflies and midges following forest harvest in nearby streams (Noel et al. 1986, Wilkerson et al. 2010).

Research Needs

We do not know how the change in nutrient concentrations across time affects stream biogeochemical processes and possibly animal populations. Indeed, if recent trends continue, streams will become more oligotrophic with lower nutrient and solute concentrations (Likens and Buso 2012). It is unknown how much this oligotrophication signals a return to natural conditions that existed before industrialization. It is possible that the temporal and spatial variation in N and P concentrations affect stream biota much less than other factors, such as geomorphic change from forest harvest, acid precipitation, and recovery from these disturbances. However, this idea is speculative given that relatively little is known about what “natural” concentrations of stream nutrients and biological communities originally existed in these streams because systematic measurements of these stream conditions did not occur until after stream chemistry had already been perturbed by acid precipitation and forest harvests (Likens and Buso 2012).

Potential Utility to Water Quality Regulatory Agencies

Nutrients can be a significant pollutant of lakes, estuaries, and coastal oceans, impairing both aquatic life and human uses. Nutrient management at the watershed scale using the total maximum daily load (TMDL) concept has been difficult to implement because of the uncertainty of source contribution of different land uses. HBEF research could serve the need to model nutrient outputs from forested watersheds under different forestry management for N and P, and air pollution loading of N. For example, already existing research findings and data from Hubbard Brook would be useful for representing the quality of water coming from forested headwater streams in models underlying the current Lake Champlain TMDL and possibly for other regionally important water quality regulatory issues.

Recently, the U.S. Environmental Protection Agency has been urging the states to develop nutrient criteria for lotic systems. Compared with lakes, thresholds of N and P enrichment for streams that adversely affect the aquatic life by altering the species composition of algal, macroinvertebrate, and fish communities are much less clear. HBEF research has the potential to contribute science on the controls on stream nutrient concentrations based on loading of nutrients under different forest management scenarios. It would be beneficial, for example, to show how much canopy removal or thinning affects stream nutrients and biological responses under different forest cutting scenarios; however, forest cutting at HBEF has not examined the effects of thinning.

Existing long-term stream monitoring data from reference watersheds at HBEF could be useful when regulatory agencies use the alternative method for setting nutrient criteria based on values obtained from minimally disturbed sites (Buck et al. 2000). In addition, the long-term decline in NO_3^- , measured in HBEF reference streams, is scientific evidence that background nutrient conditions can change over time, even in minimally disturbed watersheds. A better understanding of what mechanisms control such change might be useful to regulatory agencies when they grapple with the question of how to set water quality standards when baseline stream conditions may be changing under the influence of regional or global drivers such as climate or air pollution.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Studies at HBEF have found that calcium (Ca) dynamics have changed during the past century owing to the well-understood phenomenon of acid precipitation. High levels of acidity in precipitation in the northeastern United States, before about 1990, caused HBEF streams to be acidic during much of the period of biogeochemical record. With the implementation of more stringent regional air pollution controls beginning in 1970, particularly with respect to sulfur, the acidity of precipitation has decreased and streams are recovering in the sense that pH has been increasing. Evidence suggests, however, that recovery of other aspects of stream chemistry from acid precipitation will be delayed because much of the Ca that was formerly in forest soils was leached away during the decades of high precipitation acidity (fig. 3.4). Calcium concentrations in streams are continuing to decline at HBEF because of declining inputs (Hedin et al. 1994) and because the pool of Ca in soils that is available for leaching has been greatly reduced (Likens et al. 1996, 1998). These changes have likely altered stream ecosystems; below we detail some studies examining the effect of Ca and pH, independent of the effects of NO_3^- , in streams at HBEF.

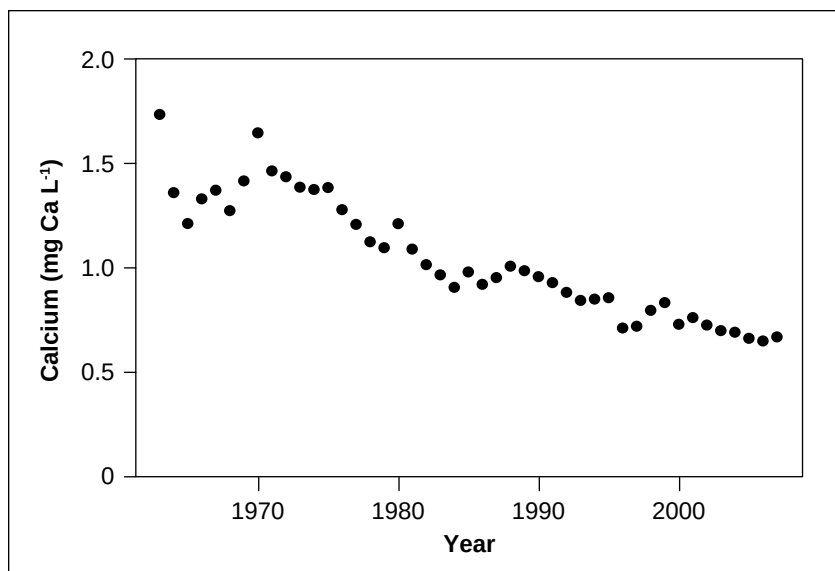


Figure 3.4—Time series of annual volume-weighted dissolved calcium (Ca) concentrations in stream water from a watershed at Hubbard Brook Experimental Forest shows strong decline through time as Ca is leached from forest soils. Data are from Likens (2012).

Findings From Studies

Streams can strongly regulate Ca^{2+} transport and storage at a range of timescales because Ca^{2+} can chemically sorb to the stream sediments (Hall et al. 2001b, Nezat et al. 2010). Stream acidity, measured as pH, mediates the amount that stream benthos can sorb Ca^{2+} , with more Ca^{2+} sorption at higher pH (Hall et al. 2001b). However, despite variation in stream Ca^{2+} concentrations and the ability for streams to regulate Ca^{2+} , there was little biological response of the WS 1 stream to added Ca^{2+} (Likens et al. 2004).

In contrast to the minimal effects of Ca^{2+} concentrations on stream biology, acidification has strongly affected streams. An experimental acid addition to Norris Brook caused large-scale drift of invertebrates and a subsequent algal bloom (Hall et al. 1980). Long-term changes to fish populations are likely due to stream acidification (Warren et al. 2008). Two fish species, slimy sculpin (*Cottus cognatus*) and eastern blacknose dace (*Rhinichthys atratulus*) are likely extirpated from HBEF because of acidification (Warren et al. 2008).

Cross-Site and Regional Studies

There have been no cross-site studies of the effects of Ca on streams that include HBEF.

Responses to Management

Investigators added Ca in the form of CaSiO_4 , the mineral wollastonite, broadcast by helicopter to WS 1 in 1999 to investigate how decades of Ca leaching may have altered biotic processes such as forest productivity. This experiment found the added Ca altered Ca biogeochemistry and forest response (Battles et al. 2014, Cho et al. 2012, Juice et al. 2006). There have been no measurements of stream ecological properties in response to this long-term experiment. Separate, earlier studies, examining biotic response to Ca addition, found little effects (Hall et al. 2001b, Likens et al. 2004), and there have been no long-term studies of stream biological response to this manipulation.

Research Needs

To assess the long-term effects of acid precipitation, it will be necessary to monitor stream biological changes through time to estimate response to acidification and loss of base cations such as Ca. Stream ecosystem response to the watershed 1 CaSiO_4 addition would be particularly fruitful. Sites such as HBEF could serve as sentinel sites for small headwater streams (Lowe and Likens 2005), with increased monitoring of nutrients, flow, temperature, and biological processes across a regional network of headwater streams.

Potential Utility to Water Quality Regulatory Agencies

There has been a tremendous amount of research into acid precipitation, its effect on waterbodies, and regulation to control this phenomenon (Hall et al. 1980, Schindler 1988). We will not cover this topic here.

At this time, most TMDL models for acid precipitation are using sulfur as the modeled pollutant, in part because it is difficult to model N in all its forms and biogeochemical transformations. However, Ca may be a limiting factor for sensitive crustacean and molluscan invertebrates, especially in lakes. Some lakes receive substantial inflows from headwater streams with chemical characteristics similar to those at HBEF. Scientific knowledge about the Ca dynamics in these streams may be useful for modeling the recovery of these lakes from the effects of past acid precipitation. For example, this information might be useful to answer questions such as how long will it take for Ca to be restored to critical levels so as to mitigate against pH fluctuations.

Overview and Synthesis

We can draw several generalizations about stream nutrient cycling and the potential effects of nutrients in streams at HBEF. There was little biological effect of nutrients to algae, with the caveat that there have been few long-term experimental nutrient additions at HBEF that were designed to alter ecological function, and the measured range in SRP and NH_4^+ concentrations is very low. Most studies at HBEF investigated the question, “How did streams affect nutrients?” rather than the question regulators are asking: “How do nutrients affect stream ecosystem function?” In state and federal water quality laws and regulations, this question is often raised in terms of, “How do physical and chemical stressors or pollutants affect the biological integrity of a waterbody?” A notable exception at HBEF is Stelzer et al. (2003), who found increased microbial activity in response to a whole-stream, nutrient addition. Streams at HBEF can strongly regulate concentrations and exports of nutrients. This pattern is similar to that seen in other parts of the United States where removal of nutrients by processes within streams can be high (Mulholland et al. 2008, Peterson et al. 2001).

There are several information gaps of importance for regulators. Regulators are interested in how much change in stream nutrient loads is required to shift stream “biological integrity” along the biological condition gradient (Davies and Jackson 2006). This task is most often accomplished by regulators assessing a combination of algae, macroinvertebrate, and fish assemblage structure and functional attributes. At HBEF, we do not know the extent to which nutrient concentrations affect fish, macroinvertebrate, and algal populations and assemblage compositions, in large part because there is limited variation in nutrient loading across this relatively undisturbed forest. There may be thresholds along the biological condition gradient, i.e., points at which major assemblage shifts occur. For example, at the Coweeta Hydrologic Laboratory in North Carolina (chapter 14), nutrient enrichment stimulated production of a caddisfly shredder that was unpalatable to predators, causing a decoupling of predator and prey secondary production (Davis et al. 2010). Similar experiments would need to be done at HBEF to test if analogous thresholds occur at HBEF, or whether lower organic matter standing stocks at HBEF (Hall et al. 2001a) might preclude such a strong biological response.

Long-term nutrient addition experiments are often a good way to assess the effect of nutrients on stream assemblages. However, the results from these studies are often idiosyncratic, showing the difficulty in predicting a common set of

responses across streams (Davis et al. 2010, Slavik et al. 2004). In addition, these experiments are labor intensive. Another alternative might be to survey streams across a nutrient gradient. HBEF might participate in such a gradient study as a site with relatively low levels of stream nutrients. New statistical approaches allow investigators to assess nutrient effects on macroinvertebrates in the face of large amounts of variability driven by other sources (Yuan 2010). Such approaches may be useful in comparative studies of the effects of nutrients on stream invertebrates both within and outside of national forests.

Assuming that recent trends of declining stream nutrient concentrations in northern forests streams will continue in the future (Bernal et al. 2012), it is unlikely that nutrients in forested headwater streams will be a strong regulatory concern, despite continued atmospheric inputs, relative to other impacts, such as long-term effects of acid rain; logging; mountain development, such as wind towers and residential and ski areas; and climate change. These stressors will alter stream temperature, hydrology, and sediment derived from geomorphic changes that affect the biological integrity of these streams. Biological data on streams combined with the long-term biogeochemical record may allow sites like HBEF to serve as a long-term reference ecosystem for detecting early signs of changing stream conditions. Likely causes of aquatic impacts could include climate change and increasing stream nutrients from human activities such as low-density residential development moving into the northern forest, which can be a source of nutrients from septic leaching, lawn fertilization, and backyard agriculture.

Studies and data from HBEF have high potential to be used by regulatory agencies for two interrelated purposes: (1) to provide measurements of the range of natural variability and long-term trends of conditions in forested headwater streams that have had minimal human influences and (2) to assess effects of human disturbance, including forest land management, acidic deposition, and climate change, on relatively low-nutrient forest streams in the northeast United States. HBEF data have the advantage, in many cases, of being collected over long time periods and in a well-documented, environmental monitoring context. Additional studies of biological responses to stream nutrients would assist agencies in developing criteria for nutrient control regulations.

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Chapter 4: Ecoregion 6.2.3 Columbia Mountains/ Northern Rockies: Priest River Experimental Forest, Idaho

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Introduction

This chapter reviews and synthesizes research on factors associated with stream water quality at the Priest River Experimental Forest (PREF). In particular, it is intended to inform regional water quality regulatory agencies, such as Idaho Department of Environmental Quality (IDEQ) and Idaho Department of Lands (IDL) on PREF's available resources and its potential usefulness for conducting synthetic and field research designed to increase science-based knowledge on factors associated with stream water quality.

Research History

The PREF was established by the U.S. Forest Service (USFS) in 1911 to promote forest research. Early studies focused on the ecology of northern Rocky Mountain coniferous forests and reforestation problems that occurred after the "Big Burn," a regionwide, catastrophic, wildland fire in 1910. Over the years, USFS scientists and their partners have cooperated on long-term ecological research at the PREF. They have investigated factors influencing wildland fire, hydrology, silviculture, forest ecology, forest genetics, and the effects of insects and diseases on the health of Rocky Mountain conifers (see Graham 2004, Wellner 1976). Researchers from the University of Idaho, University of Montana, Washington State University, as well as federal, state, and Canadian land management agencies have also conducted a wide variety of studies at the PREF. Research conducted at the PREF has resulted in more than 650 publications.

Availability of Publications and Data

The PREF has been a monitoring site (site No. ID02) since 2003 within the National Atmospheric Deposition Program (NADP), which is a nationwide network that monitors precipitation chemistry, including acid rain, and is available online (NADP 2017). Streamflow data since 1939 for Benton Creek gaging dam are archived at the Moscow Forestry Sciences Laboratory in Moscow, Idaho, and the USFS Rocky Mountain Research Station (RMRS) archive and are available online (see Link et al. 2015). Daily weather records may also be accessed online (USDC NOAA 2017). Snowpack

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data collected since 1937 at Benton Meadow, elevation 710 m, and at Benton Spring (Station ID: 16A03), elevation 1470 m, are available online (see USDA NRCS 2017). Additional information on research products from the PREF are available on its website (USDA FS 2017).

Site Description

The PREF lies within the Idaho Panhandle National Forest and is administered by the RMRS, with assistance from the USFS Northern Region. The PREF headquarters is onsite and includes short-term housing for researchers, laboratory and office space, conference facilities, and an active forest nursery (fig. 4.1).

The PREF (lat. 48.351° N, long. 116.835° W) is located on federal land officially dedicated to research. It is within the moist mixed-coniferous forests of northern Idaho on the west slope of the Selkirk Mountains. The PREF encompasses 2521 ha of mountainous forest and includes major forest types found in the northern Rocky Mountains. Its elevation ranges from 671 to 1798 m. Within its boundaries there are two main drainages: Benton Creek and Canyon Creek watersheds which are tributaries of Priest River within the Columbia River basin.

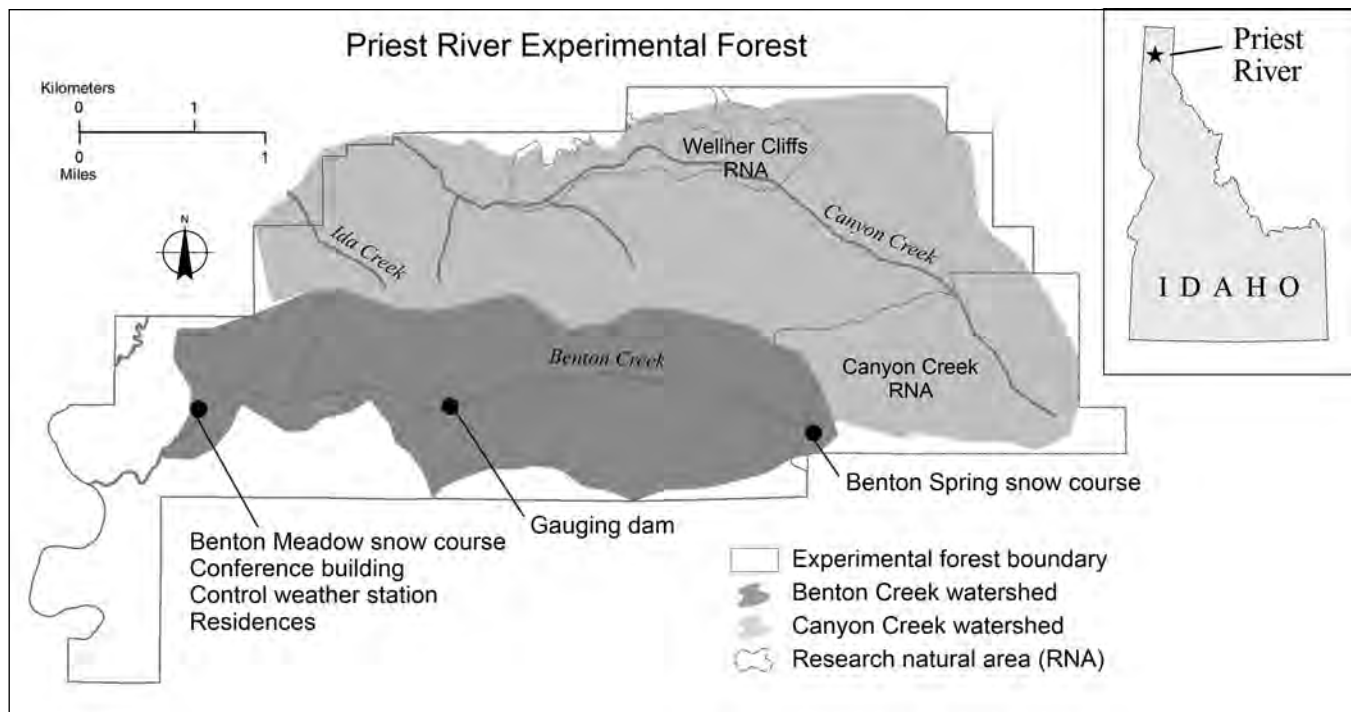


Figure 4.1—The Priest River Experimental Forest in northern Idaho (from Graham 2004).

The PREF's climate is transitional between northern Pacific coastal and continental (Finklin 1983) and resembles southeastern British Columbia's more than that of the neighboring Rocky Mountains or Cascade Range (Tinkham et al. 2015). Monthly mean temperatures at the headquarters weather station range from -4 °C in January to 18 °C in July. The average annual (water year) precipitation ranges from 817 mm at the PREF headquarters, elevation 710 m, to 925 mm at the Benton Spring rain gage, elevation 1455 m (Tinkham et al. 2015).

Soils at the PREF are derived from parent material of Belt Series bedrock that consists predominantly of gneiss and lesser inclusions of granite, sandstone, shale, and schist. Granitic bedrock is less resistant to weathering and usually has thicker soil mantles than gneiss or schist. Soils of lowland benches contain varves of silt, clay, and sand from glacial recession and outwash (McConnell 1965). Upland soil types differ with elevation and aspect. The most common soil types are (1) the Jughandle soil series, which has a coarse-loamy texture; (2) the Saltese soil series, which are mostly wet organic soils; and (3) the Springdale soil series, which have sandy-skeletal texture and a xeric moisture regime. Both Jughandle and Springdale soils contain pyroclastic material likely from the eruption of Mount Mazama, about 7,700 year BP (Zdanowicz et al. 1999).

Streams within the PREF have steep riffle-pool structure, with coarse boulder and gravel substrates and large wood in the streambed. Most first- through third-order streams are under a closed canopy of coniferous riparian vegetation consisting predominantly of western hemlock (*Tsuga heterophylla* Raf. Sarg.), western redcedar (*Thuja plicata* Donn ex D. Don), and western white pine (*Pinus monticola* Douglas ex D. Don).

About one-third of the PREF contains trees that originated following severe wildland fires in the mid-1800s and range in age from 120 to 160 years. Another third of the forest contains trees more than 200 years old, while some trees in riparian areas may exceed 300 years of age. The remaining forests consist of younger trees that have regrown after timber harvests or wildfires since the PREF was established, and of treeless alpine meadows and talus slopes. Analyses of forest cover and habitat types of the PREF found that plant communities were complex owing in part to abrupt changes in slope, aspect, and wet-to-dry habitats that promote intimately intermixed structural and successional vegetative stages among a diversity of plant species (Ferguson and Zack 2006).

The experimental forest contains a variety of actively managed and reserve areas, with ecological conditions ranging from recently manipulated to wild and pristine. There are two research natural areas (RNAs) within the PREF: Canyon Creek RNA, 395 ha, established in 1937, and Wellner Cliffs RNA, 125 ha, estab-

lished in 2006 (fig. 4.1). These RNA sites are reserved for nondestructive research, education, and maintenance of biodiversity of climax vegetation and unique ecosystems. Within RNAs, permanent research installations, and experiments that might disturb soil or vegetation are not permitted. The remainder of the PREF is available for experimental manipulation of vegetation, soil, and other ecosystem components and has received a variety of treatments.

Reference Watershed

The Canyon Creek watershed is the closest approximation to an undisturbed drainage within the PREF and has, in the past, been considered a *de facto* reference (see Rabe and Cazier 1993). This status was applied to the Canyon Creek watershed because its headwaters originate from the pristine Canyon Creek RNA, and management activity applied downstream of the Canyon Creek RNA has been historically low in frequency and scale. Specifically, in 1970, a 23-ha buffered clearcut was applied in the farthest downstream area from the headwaters within the PREF (see Snyder 1973, Snyder et al. 1975); in 1978, harvest activities removed trees for road construction of three rights-of-way; and in 2004, thirty-seven small plots, each no more than 2.7 ha and totaling 80 ha (see Jain et al. 2008), were harvested to examine effects of fuel treatments on uplands away from Canyon Creek. The relatively low management activity within Canyon Creek watershed can be attributed to its limited road access compared with the adjacent Benton Creek drainage (fig. 4.1). Rabe and Cazier (1993) used Canyon Creek's water quality to represent relatively undisturbed, forested headwater basins in northern Idaho; however, this assumed status has not been validated through empirical study. In addition, future land management activities in Canyon Creek basin and how they will affect the condition of its streams are uncertain because, with the exception of the Canyon Creek and Wellner Cliffs RNAs, the USFS has not formally committed to maintain minimal human disturbance in this basin.

Biological Responses to Stream Nutrients N and P

Issues of concern—

Overenrichment of surface waters with nutrients can negatively affect ecosystem services, including water purification, fishing, hunting, recreational tourism, forest products, and storage of greenhouse gases (see Cummings et al. 2014). The economy of northern Idaho is largely dependent on many of these ecosystem services. Therefore, degradation of the surface waters of northern Idaho could have severe impacts on both the social and economic health of this region.

Expansion of urban land use and development in northern Idaho may lead to overenrichment of surface waters owing to the potential for increased discharge of nitrogen (N) and phosphorus (P). Although most of the land in the north Idaho

counties is in public ownership, principally the USFS and the IDL, prime lake and river frontage has attracted increased seasonal and full-time residences, and resorts on private lands and leases from public agencies.

Surface water quality may also be threatened by large fires, which have occurred more frequently in northern Idaho in recent years owing, in part, to ongoing climate change (see Abatzoglou and Williams 2016). This is a concern because short-term increases in N and P in surface waters occur after disturbances to forest vegetation such as wildland fires and timber harvests. Retention of streamside vegetation as riparian buffers can reduce impacts of forest cutting on water quality and fish habitat (Kreutzweiser et al. 2005, Macdonald et al. 2003, Wilkerson et al. 2006), but severe wildland fires sometimes burn riparian vegetation along with the adjacent forest. Although, as burned lands revegetate several years after fires, water quality in streams returns to predisturbance conditions (see Minshall et al. 1997).

Findings From Studies

Baseline survey studies in Canyon Creek in 1993 and 1995 were conducted to describe the biotic and abiotic characteristics of this relatively undisturbed headwater stream (Rabe and Catts 1995, Rabe and Crazier 1993). The 1993 survey measured physical and chemical stream parameters in concurrence with stream macroinvertebrate community at the family level on the upper reaches of Canyon Creek. Chemical analyses found nitrate/nitrite levels of 0.2 mg/L and phosphate (PO_4^{3-}) were below detectable limits, although those limits were not reported. Stream sampling of the macroinvertebrate community found 33 taxa, which was similar to other reference streams. Rabe and Catts (1995) conducted a second biological survey of Canyon Creek in a reach downstream from the 1993 study. This study focused on surveying macroinvertebrate communities at the family level and stream physical characteristics but did not include chemical analyses of stream water. They found a diversity of 40 taxa, which was substantially different from the diversity observed in their Upper Canyon study as indicated by a 52 percent index of similarity between sites. Survey results (Rabe and Catts 1995, Rabe and Crazier 1993) provide a benchmark of stream conditions in two reaches of this relatively undisturbed mountain basin.

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

A number of environmental factors that may directly or indirectly influence surface water quality and associated biological responses have been monitored and studied at the PREF, including weather (1911 to present), streamflow (1933 to present), snow accumulation (1937 to present), and atmospheric deposition chemistry (2003 to present). For example, Tinkham et al. (2015) analyzed long-term trends from 1912 to 2015 in streamflow, air temperature, and snowpack at the PREF. They found that

the date of peak flow has shifted 3.75 days earlier each decade since 1950, and that there were significant trends of increasing mean annual temperature, decreasing snowpack, and earlier spring warming through the past century at the PREF (fig. 4.2). Collectively, these trends support the conclusion that climate has changed at the PREF over the past century.

The NADP precipitation chemistry monitoring at the PREF provides a record since 2003 of atmospheric deposition of nitrate (NO_3^-) in terms of both concentrations in precipitation and area loading. Nitrate deposition has shown large increases during years in which large, late-summer wildland fires occurred in the region (fig. 4.3). Measurements of orthophosphates (PO_4^{3-}) in atmospheric deposition only occasionally registered above the detection limit of 0.009 mg/L. Even when detectable, deposition of PO_4^{3-} is considered negligible at the PREF and is not included in the NADP annual summaries.

In the study of environmental pollutants, critical loads are science-based quantitative thresholds that define limits of atmospheric deposition below which significant harmful effects to the environment are not expected (cf. Nilsson and Grennfelt 1988). Critical loads for N, specific to the PREF and northern Idaho, have not been directly measured. However, critical loads of 2.7 to 9.2 kg N/ha/yr (Geiser et al. 2010), based on changes in lichen, and 5 to 7 kg N/ha/yr (Lilleskov 1999 as cited in Pardo et al. 2011), based on ectomycorrhizal fungi, both measured in the maritime forests of western Washington, have been used as proxies to estimate critical loads in northern Idaho. By comparison, McMurray et al. (2015) reported critical loads of 4 kg N/ha/yr based on changes in lichen assessed in northwestern Wyoming and eastern Montana, where climate is drier and more continental than at PREF. Comparing these estimated critical loads with the currently observed rate of atmospheric deposition of N at the PREF of 1.5 kg N/ha/yr suggests that this ecosystem has not been harmed by current levels of N deposition.

Cross-Site and Regional Studies

Atmospheric deposition data collected at the PREF have been included in national and regional analyses and maps regularly produced by the NADP, National Trends Network (NTN). These analyses have shown that atmospheric deposition of N and P at the PREF has been low compared to most sites in the continental United States and are typical of wildland sites in the northern Rocky Mountains. Atmospheric deposition measured at the NADP site in Glacier National Park (MT07), in northern Montana, showed similar high nitrate deposition in years when the region had large wildland fires. Climate and streamflow data from the PREF were used in long-term multisite analyses of ecological effects of climate change by Peters et al. (2013).

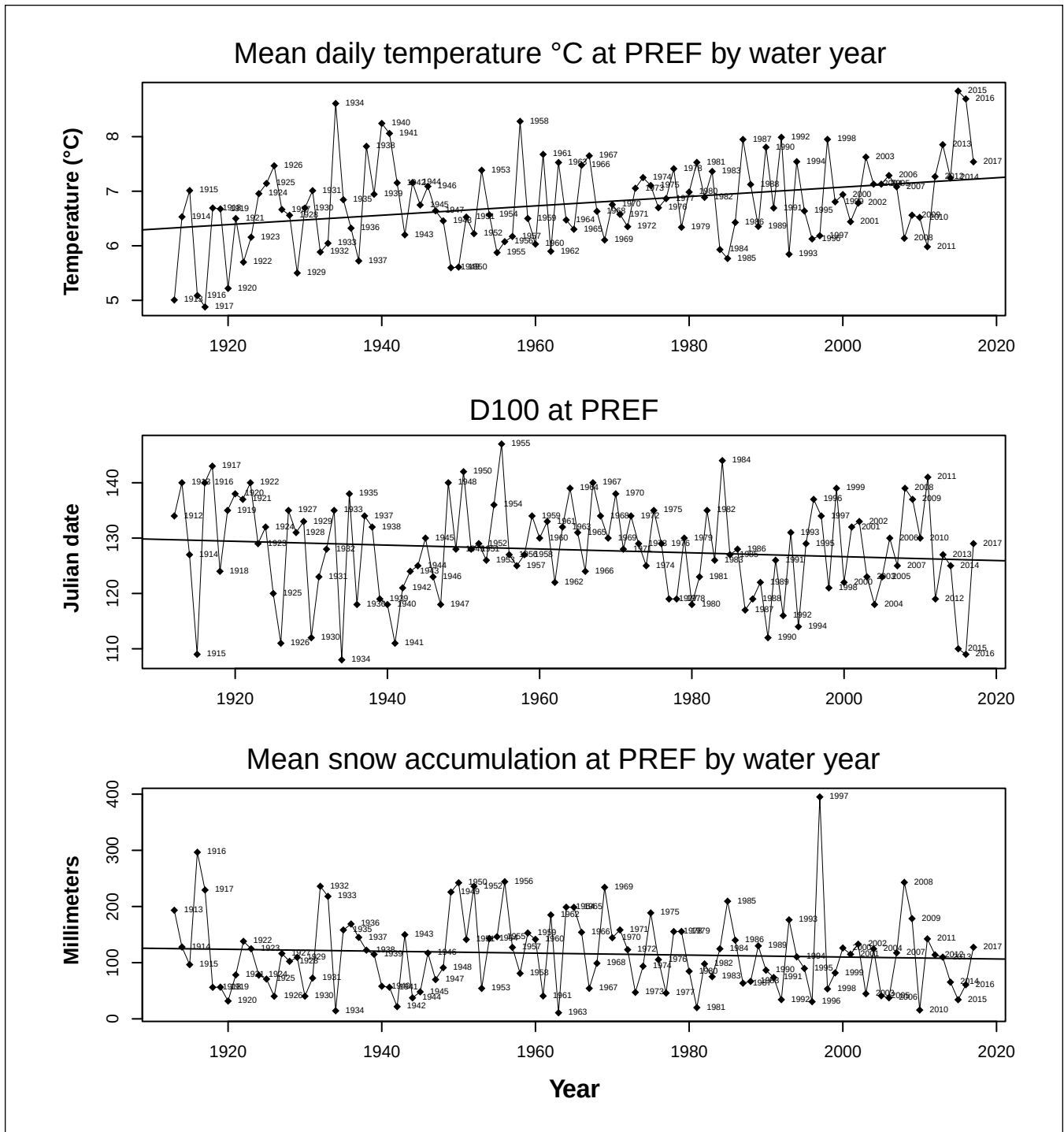


Figure 4.2—Climate variables from 1912 through 2015 at the Priest River Experiment Forest (PREF). D100 is a measure of the timing of spring warming calculated as the first Julian date on which cumulative degree-days in excess of 5 °C, beginning on January 1, are greater than 100.

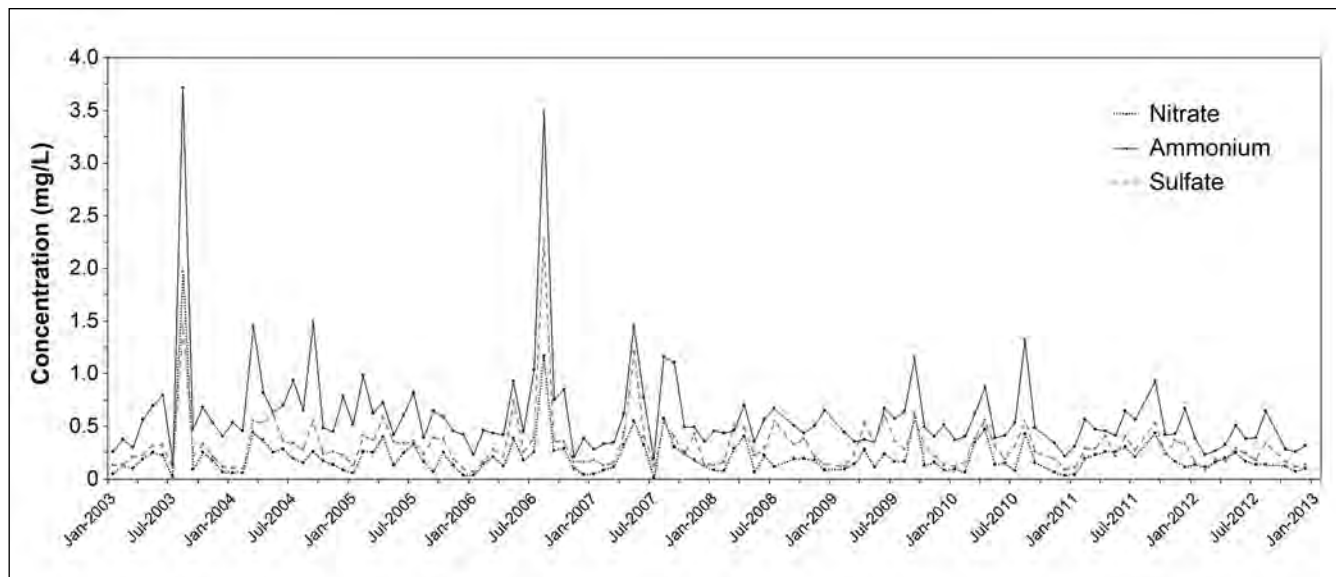


Figure 4.3—Concentrations of nitrate, ammonium, and sulfate in atmospheric deposition collected at the Priest River Experimental Forest National Atmospheric Deposition Program site from 2003 to 2012. The two outlier peaks in the deposition of nitrate in the summers of 2003 and 2006 coincided with large wildland fires in the region that occurred in late summer in both years (from Tinkham et al. 2015).

Dose-Response Studies

Dose-response studies have not been conducted at the PREF.

Responses to Management and Natural Disturbances

Only a few studies of limited scope have examined effects of harvesting on stream nutrients at PREF. Snyder (1973) and Snyder et al. (1975) examined the impact of forest harvest and slash burning treatments within the cedar-hemlock-grand fir ecosystem on stream water quality in Canyon Creek, Ida Creek, and Benton Creek (fig. 4.1) at the PREF. Their research used monitoring of stream water chemistry upstream, on, and downstream from, treatments over a 21-month period following treatment application. The treatments ranged in size from 2.6 to 44 ha with buffers ranging from 30 to 61 m. Results showed that NO_3^- concentrations were not detectably different between sites upstream (control) and downstream from treatments although NO_3^- was eight times greater on treatment sites. Significant increases were detected downstream of the treatments for pH, electrical conductivity, turbidity, and suspended solids, although increases were not consistent among sites. Phosphorus and biological responses were not measured.

There is a long history of PREF studies of the effects of timber cutting on snow-pack and water yield. Peak spring flows from snowmelt may affect water quality by increasing bank erosion and suspended sediment. Packer (1962) used PREF data

to develop a model that accounted for 91.6 percent of variation in maximum snow water equivalent (SWE) based on elevation, aspect, snowpack density, and snowfall. He also reported that SWE increased with lower canopy density, with the highest SWE on clearcuts. From PREF studies, Haupt (1979a) reported that decreased canopy interception caused most of enhanced snow accumulation on clearcuts, and that this effect could persist for up to 34 years postharvest as canopy recovered. Haupt (1979b) further reported that north-facing clearcuts had greater SWE and contributed more to winter rain-on-snow flooding and spring peak flows than did south-facing clearcuts. He also found that spring snowmelt occurred earlier on south-facing clearcuts than in uncut forest and suggested that a mix of cut and uncut forest might reduce spring peak flows in south-facing basins by desynchronizing snowmelt. More recently, Elliot and Glaza (2009) monitored runoff and sediment loads from 10 small PREF watersheds (<7 ha) that received different harvesting treatments. Only an untreated watershed had perennial flows and, as expected, produced very low sediment yield. Dobre et al. (2011) studied the same watersheds and found large increases in SWE and snowmelt rates on the treatment that most drastically reduced canopy, a simulated wildland fire with salvage logging, but only minor effects on snowpack in treatments with less canopy reduction.

MacPhee and Cheng (1976) examined the effects on aquatic insects of a silicone-based chemical treatment that contained dimethylsiloxane polymers intended to increase soil moisture and water yield by inhibiting transpiration. It was hypothesized that the silicone emulsion might affect predator species of aquatic insects either directly from toxic exposure to the applied chemicals, or indirectly from loss of their food base. A spray of 375 L/ha of 5 percent antitranspirant was applied by helicopter directly to tree foliage on a 26-ha subwatershed of Benton Creek. Another untreated 20-ha subwatershed served as a control. Their results showed that aerially spraying the antitranspirant had little or no acute effect on aquatic insects for up to 96 hours after the treatment. No other study at the PREF has examined stream biological responses to management or research treatments.

No studies have been conducted to assess impact of natural disturbance on stream N and P within the PREF. Large-scale natural disturbances have been rare since the establishment of the PREF. The only significant wildland fire occurred in 1922 and burned about 160 ha on the Fox Creek drainage, south of the Benton watershed. Since then, spot fires from lightning have been quickly extinguished by effective fire suppression before any exceeded 2.8 ha. Insect-related tree mortality within the PREF has been typical of forests in the region. From 1998 to 2000, there was an outbreak of Douglas-fir bark beetles (*Dendroctonus pseudotsugae*) that seriously damaged Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands.

Management response to this disturbance was a series of partial cuttings that removed infested or dying trees, followed by underburning and planting. These activities took place at mid-slope sites, presumably far enough from Benton and Canyon Creeks to have little or no effect on stream water quality, although no studies or monitoring were conducted to assess potential impacts.

Reliability and Limitations of Findings

Datasets and research results from the PREF can probably be applied to other forested headwater basins that have similar land uses in the northern Rocky Mountains. At sites that are dissimilar to the PREF, or where a high degree of accuracy is needed, a good option might be validation monitoring or experiments to test how well results from the PREF are representative of local conditions.

Research Needs

The highest priority need for the regional regulatory community is increased science-based knowledge on the impacts of timber harvesting on suspended sediments, streambank stability, and water temperature. This knowledge is needed, for example, to assist Idaho Department of Lands and its partners with validation or redesign of current Idaho state Forest Practices Act rules that protect water quality. The PREF might be used to conduct experimental studies to address this priority need.

Studies intended to test the effects of vegetative treatments on water quality at the PREF may, however, face two limitations: (1) topography and (2) INFISH (Inland Native Fish Strategy), (USDA FS 1995), which was incorporated into the 2015 Idaho Panhandle National Forest Plan (USDA FS 2015). Topography at the PREF may pose a challenge for study designs because it contains only two main streams with each stream having few definable tributaries. As a consequence, it may be difficult to identify enough subwatersheds for paired comparisons of treatment effects on water quality. Use of a nested study design approach might be necessary to overcome this limitation. INFISH includes riparian goals, riparian management objectives, standards, and guidelines that apply to management activities on national forests lands. Within PREF, INFISH requires riparian-dependent resources to receive primary emphasis within areas called riparian habitat conservation areas (RHCAs) that are adjacent to aquatic features. Management activities within RHCAs are subject to specific standards and guidelines intended to maintain the integrity of aquatic ecosystems and processes. This includes protection of associated fish habitats for west slope cutthroat trout (*Oncorhynchus clarkii lewisi*), which is a Northern Region sensitive species (IDFG 2019), and bull trout (*Salvelinus confluentus*), which is listed as threatened under the Endangered Species Act of 1973 (16 U.S.C. 1531-1536, 1538-1540) in accord with the “Biological Opinions”

for bull trout (USDI FWS 1998). INFISH requirements may limit study designs because of restrictions on forest harvesting practices within RHCAs. For example, studies of forest thinning in stream buffers on federal land would be subject to INFISH requirements within RHCAs that extend a minimum of 91 m from perennial fish-bearing streams. Although, in principal, studies of forest harvest activities may be proposed within RHCAs, in practice, such studies would more likely be delayed or blocked by legal challenges under federal statutes than forest harvest activities outside of RHCAs. As a result, investigating tree harvesting with buffers less stringent than INFISH would probably be more feasible on private or state lands where state laws apply. Examples of management experiments performed on private lands were the studies of state-mandated buffers at the Mica Creek Experimental Watershed, where effects of road building and timber harvest on suspended sediment loads (Karwan et al. 2007), nutrient dynamics (Gravelle et al. 2009a), peak stream temperatures (Gravelle and Link 2007), and aquatic macroinvertebrate populations (Gravelle et al. 2009b) were investigated.

Management practices that comply with INFISH guidelines might be tested for effects of harvesting and other vegetative treatments on water quality at the PREF. Results of such experiments might be useful to land managers and regional regulators to better understand how management of federal lands affects water quality in the region as a whole, particularly given that federal lands make up a substantial portion of the land base in the northern Rocky Mountains.

Additional science-based knowledge that might be addressed through research at the PREF that is presently of lower priority to the regulatory community includes increased understanding of how stream nutrient concentrations and biological communities are affected by forest harvesting practices.

Potential Utility to Water Quality Regulatory Agencies

Long-term and ongoing monitoring datasets (weather, streamflow, snowpack, NADP) are immediately available and perhaps the most valuable asset that the PREF offers to address the knowledge needs of regional regulators. These data can be used to interpret the results of short-term studies by providing a baseline of water quality and its range of natural variability from day to day and season to season in the relatively undisturbed forest of Canyon Creek watershed.

PREF's long-term weather observations, snow surveys, and streamflow datasets provide evidence of local climate change and its impacts on ecosystem processes (e.g., Tinkham et al. 2015). These datasets can be used by regulatory agencies to assess how regional stream conditions may be changing under ongoing climate change. For example, the rising trend of mean annual temperature, decreasing snowpack, and increasingly earlier spring warming (fig. 4.2) may advance regional snowpack melt

and boost peak runoff. These changes have many potential implications for water quality and aquatic processes (see Burns et al. 2011) that may be linked, for instance, to earlier onset of high flows in spring and low flows in summer and associated changes in streambank stability and the timing of surface water turbidity.

The IDEQ might benefit if it implemented aquatic biological monitoring at the PREF as part of its ongoing aquatic biology survey and water quality monitoring programs. By implementing its own monitoring at the PREF, IDEQ would ensure that results would be comparable with aquatic monitoring practices elsewhere in the state. Results from aquatic biological monitoring, particularly in relatively undisturbed Canyon Creek watershed, could also be used to detect whether stream conditions have changed in response to drivers such as climate change since they were last measured at the PREF decades ago (see Rabe and Catts 1995, Rabe and Cazier 1993). An example of a water quality monitoring and assessment program that might be advantageous for IDEQ to implement at the PREF is its Beneficial Use Reconnaissance Program (BURP) (IDEQ 2019a). This program is carried out by seasonal teams that have conducted aquatic biological surveys and collected stream habitat data throughout Idaho since 1993. Results of BURP monitoring at the PREF might be included in the Idaho Integrated Report (IDEQ 2019b), which summarizes the condition of waters throughout Idaho.

Key points:

- Long-term and ongoing monitoring at the PREF includes data on stream-flow, stream water chemistry, weather, snowpack, atmospheric deposition chemistry, and vegetation composition. These datasets are immediately available and are a valuable asset that the PREF offers to support research on stream biological responses to N and P or other factors associated with stream water quality.
- Studies at the PREF on effects of forest management have primarily focused on the terrestrial components of the ecosystem, although a few studies have examined effects of harvesting on stream nutrients.
- Biological responses to stream N and P have not been studied at the PREF; however, stream surveys at the PREF have measured the composition of aquatic communities under low, ambient stream water concentrations of N and P characteristic of relatively undisturbed watershed conditions.
- The highest priority need of the regulatory community that may be addressed by research at the PREF is an increase of science-based knowledge on the effects of forest harvesting methods on stream water quality and stream channel stability. However, such studies at PREF would be constrained by topography and INFISH rules.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

There are currently no issues of concern related to nutrients other than N and P across the northern Rocky Mountain region. However, in some localized areas, drainage from active or abandoned mines or mine spoil disposal sites may degrade surface water quality by introducing high levels of suspended sediments, acidity, sulfate (SO_4^{2-}), and dissolved iron (Fe), magnesium (Mn), and toxic heavy metals (see Reece et al. 1978). Where it occurs, mine drainage may detract from beneficial uses such as fish habitat, drinking water supply, and water-contact recreation. The PREF has not been subjected to mining and spoil disposal disturbances, so its streams might be used as baseline for conditions in the absence of mining-related disturbances.

Findings From Studies

Rabe and Cazier (1993) analyzed Canyon Creek stream water for nutrients other than N and P, including calcium (Ca^{2+}), and magnesium (Mg^{2+}) concurrently with surveys of stream macroinvertebrates. They reported potassium (K^+), sodium (Na^+), aluminum (Al^{3+}), Fe, and zinc (Zn) were below the detectable limits of the analyses but gave no estimates of specific detectable limits. They also reported water temperature, pH, alkalinity, conductivity, turbidity, total dissolved solids, and fecal coliform.

Atmospheric deposition of several nutrients other than N and P have been monitored at the PREF since 2003 as part of the NADP network (see NADP 2017). Measurements consist of wet deposition that is collected weekly and analyzed for Ca^{2+} , Mg^{2+} , K^+ , Na^+ , chloride (Cl^-), SO_4^{2-} , pH, and conductivity. Current levels of deposition of these nutrients at the PREF are low.

Responses to Management and Natural Disturbances

Few studies have examined the treatment response of nutrients other than N and P in streams at the PREF. Snyder (1973) and Snyder et al. (1975) included nutrients other than N and P in their studies of effects on stream water of clearcutting and slash-burning treatments. Their analyses of stream chemistry included bicarbonate (measured as $\text{Ca}(\text{HCO}_3)_2$), SO_4^{2-} , Cl^- , Na^+ , K^+ , Mg^{2+} , and Ca^{2+} , as well as electrical conductivity, turbidity, and filterable solids. The management treatments they studied (see previous section under “Management Treatment Response Studies”) did not affect these chemical constituents except for carbonate, which increased. Effects of natural disturbances on nutrients other than N and P and associated biological responses have not been studied at the PREF.

Reliability and Limitations of Findings

The few datasets and research results for the PREF related to nutrients other than N and P may apply to other forested headwater basins that have similar land uses in the northern Rocky Mountains. At sites that are dissimilar to the PREF, or where a high degree of accuracy is needed, validation monitoring or experiments might be considered to test how well results from the PREF predict local conditions.

Research Needs

Presently, there are no science-based knowledge needs that are a priority for the regional regulatory community related to nutrients other than N and P that could be addressed through research at the PREF.

Potential Utility to Water Quality Regulatory Agencies

The findings on the effects of forest management on streams (Snyder 1973, Snyder et al. 1975) may be useful for developing water quality standards and best management practices for forestry operations. The surveys of stream invertebrates and nutrients other than N and P in an undisturbed stream (Rabe and Cazier 1993) may provide data that agencies can use as a baseline for developing water quality criteria and desired future condition when restoring affected surface waters.

The NADP data available for atmospheric deposition of nutrients at the PREF are useful for assessing whether atmospheric inputs are affecting the water quality of the region. These data provide status and trends of deposition of a broad spectrum of potential pollutants and might serve as early warning if, in the future, deposition of a pollutant such as SO_4^{2-} were to approach levels that could affect water quality.

Key points:

- Stream surveys of relatively undisturbed Canyon Creek (Rabe and Catts 1995, Rabe and Cazier 1993) have documented physical and biological characteristics and ambient nutrients other than N and P, which might serve as a baseline for developing water quality criteria.
- Few studies have examined the treatment response of nutrients other than N and P in streams at the PREF.
- Atmospheric deposition monitoring at the PREF could serve as early warning if, in the future, deposition of pollutants from the air were to approach levels that could affect water quality.

Overview and Synthesis

The PREF contains headwater stream basins that are typical of mixed-conifer forests of the northern Rocky Mountains. Long-term monitoring at the PREF has included streamflow, stream water chemistry, weather, snowpack, atmospheric deposition chemistry, and vegetation composition. A small number of short-term studies of streams have been conducted at the PREF, including effects of forest harvesting on stream chemistry in the 1970s. Surveys of stream macroinvertebrate, water quality, and physical habitat measurements were simultaneously conducted in the 1990s in relatively undisturbed Canyon Creek, which served as a de facto reference basin. However, the future status of Canyon Creek basin is uncertain because it has not been officially reserved to be managed for minimal human disturbance.

Research at the PREF can provide regional regulators with a more comprehensive understanding of the effects of forest management and other disturbances on water quality for northern Idaho. However, experimental studies at the PREF will likely be constrained to study designs such as nesting of watersheds to compensate for the PREF's limited number of subwatersheds. Investigations within RHCA's within PREF will also likely be required to comply with relatively stringent INFISH requirements.

PREF's long-term and ongoing ecosystem monitoring and past stream surveys of relatively undisturbed forest in the Canyon Creek basin are ideally suited to support research designed to provide on-the-ground evidence of "potential natural vegetation," which would be useful for practical purposes such as development of total maximum daily loads, water quality criteria, and best management practices.

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Chapter 5: Ecoregion 6.2.7 Cascades: H.J. Andrews Experimental Forest, Oregon

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Introduction

This chapter is a review and synthesis of research on stream nutrients from the H.J. Andrews Experimental Forest (HJA) located in the western Cascade Mountains of Oregon. This research includes studies, some of which originated in the 1960s, in streams through reference forests and harvested watersheds. In addition to providing foundational information for researchers and managers, the information in this chapter serves to inform national and regional water quality regulatory agencies about results of relevant scientific studies at HJA. The chapter also identifies questions of potential interest to regulatory agencies involving processes of transport, transformation, and uptake of nutrients that could be addressed at HJA.

In the Pacific Northwest, many species of anadromous fish are declining and at risk of extinction. As a result, several species of anadromous salmon and trout (salmonids) have been listed under the federal and state of Oregon Endangered Species Acts (16 U.S.C. 1531-1540; ORS 496.171-496.192). Causes of these species' decline include deterioration of critical habitat conditions in the region's rivers and streams. Several of these critical habitat features are related to water quality, including stream water temperature and sediment load. Streamside vegetation plays an important role in providing favorable habitat for these fish by providing shade, erosion control, and serving as a source of instream large wood. Measures to protect and restore habitat for these at-risk species have had economic and social impacts across the region.

Site Description

The HJA is situated in the western Cascade Range of Oregon (lat. 44° 14' N, long. 122° 10' W) (fig. 5.1) in the 6400-ha drainage of Lookout Creek. Elevation ranges from 410 m to 1630 m. The climate is cool and wet in winter and warm and dry in summer. Annual precipitation averages 2130 mm at low elevation and increases with altitude (Post and Jones 2001). Eighty percent of precipitation falls

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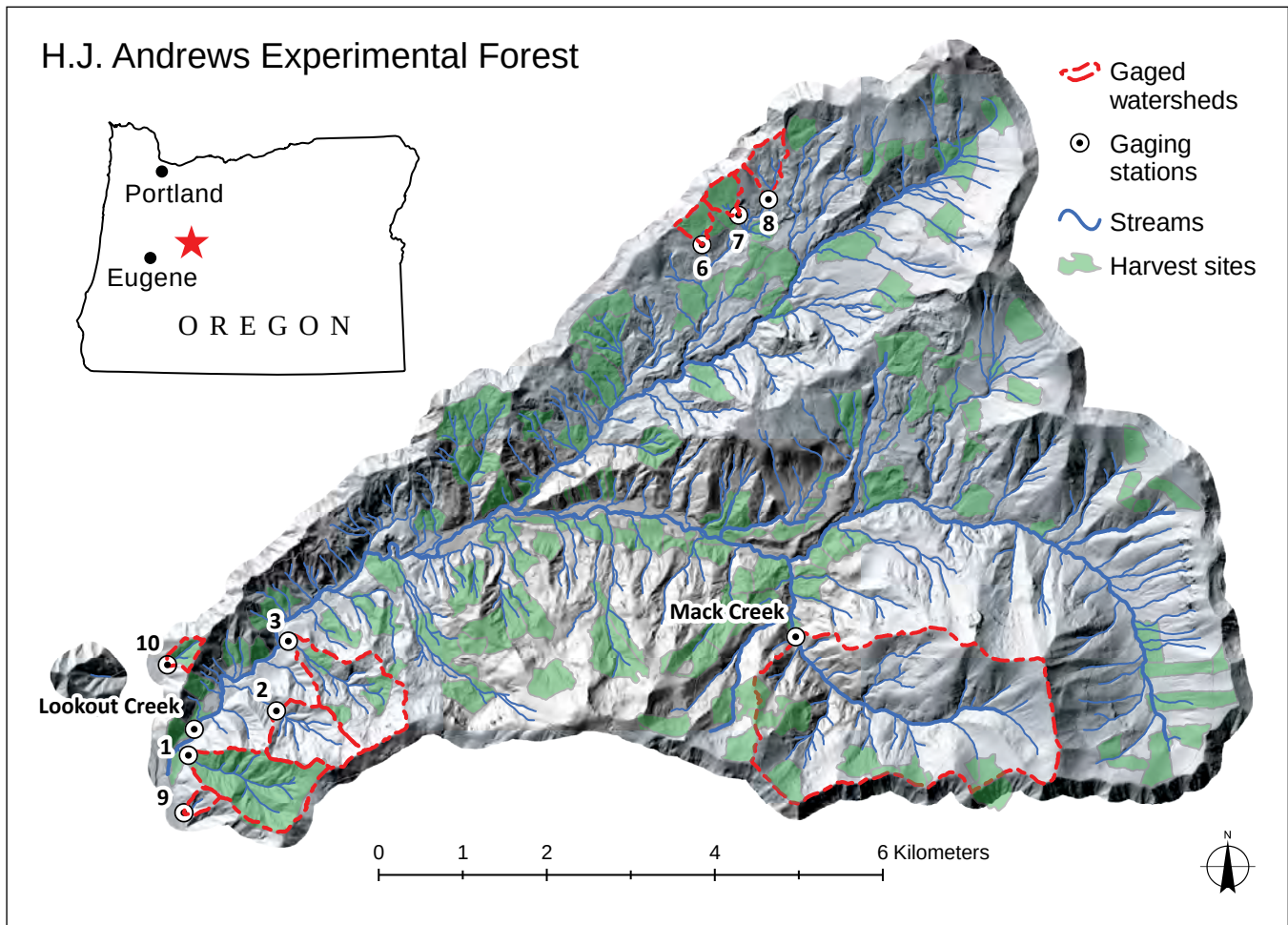


Figure 5.1—H.J. Andrews Experimental Forest and its small study watersheds that have been monitored for decades.

between October and March. Rain predominates at low elevations and snow at upper elevations. Very little rain falls during summer, and streamflows generally decline from June through September.

Forest and riparian soils are formed from highly weathered volcanic parent material and have silt textures, high rock fragment content, and moderate organic horizons (Dyrness 1969). Because of the steep topography in these basins, shallow soils with little profile development predominate (Dyrness 1969, Rothacher et al. 1967). Soil temperatures generally remain above freezing.

Vegetation in the forest is primarily coniferous, dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Outside areas where vegetation has been harvested or experimentally manipulated, stands have two general age classes, 180 and 500 years old, that developed after wildland fire. Riparian areas contain deciduous tree species, including red alder (*Alnus rubrus* Bong.) at lower elevations, and bigleaf maple (*Acer macrophyllum* Pursh) and vine maple (*A. circinatum* Pursh) in riparian areas across elevations. Stream channels are steep, and many have a history of small debris flows.

Research History

The HJA was established in 1948 with the goal of studying effects of timber harvest on water quality, quantity, and forest regeneration dynamics after harvest. Eight small watersheds were established between 1950 and 1965 as paired watershed studies with streamgages for hydrologic measurements and sediment collection basins. Two larger streams were also gaged (Johnson and Rothacher 2018). Regular monitoring of stream water nutrients was added at all but one stream gage (table 5.1). Atmospheric deposition chemistry and fluxes have been monitored from 1980 to present as part of the National Atmospheric Deposition Program (NADP) network (NADP 2019). Watersheds (WS) WS 2, WS 8, and WS 9 are reference basins with undisturbed forest cover.

From 1962 to 1984, multiple forest harvesting experiments were carried out at HJA to observe effects of simulated forest management practices on stream

Table 5.1—Descriptions of H.J. Andrews Experimental Forest gaged watersheds, including dates of initiation of stream gaging and duration of stream chemistry sampling^a

Watershed	Gaged area	Gage elevation	Maximum elevation	Forest origination period	Management history	Stream gage start	Stream chemistry start
	<i>Hectares</i>	<i>Meters</i>	<i>Meters</i>				
1	96	439	1027	~AD 1500	100% clearcut 1962–1966; burned 1967; no roads	1952	2003
2	60	545	1079	~AD 1500	Reference, no harvest	1952	1981
3	101	476	1080	~AD 1500	25% patch clearcut 1963; 6% roads 1959	1952	—
6	13.0	878	1029	~AD 1700–1850	100% clearcut 1974; 9% roads	1963	1971–1987; restart 2002
7	15.4	918	1102	~AD 1700–1850	60% overstory harvest 1974; remaining canopy removed 1984; 12% noncommercial thin 2001	1963–1987; restart 1995	1971–1987; restart 2002
8	21.4	962	1182	70% after fire ~AD 1850, 30% ~AD 1500	Reference, no harvest	1963	1971
9	8.5	426	731	~AD 1500	Reference, no harvest	1968	1968
10	10.2	461	679	~AD 1500	100% clearcut 1975	1968	1968
Mack	580	755	1626	95% ~AD 1500, 5% after ~AD 1850	13% harvest; road on ridgeline	1979	1980
Lookout	6242	422	1627	40% after fire ~AD 1500 ; 25% after fire ~AD 1850	25% harvest 1952–1985; 10% roads	1949	2005

— = not available.

^a More details are available at <https://andrewsforest.oregonstate.edu/research/infrastructure/watersheds>.

water quantity and quality (table 5.1). These experiments were conducted on gaged watersheds, and water chemistry and suspended sediment (Johnson and Fredriksen 2017) and stream temperature (Johnson and Gregory 2016), were monitored on the streams draining the treated watersheds.

Ecosystem studies at HJA began during the International Biological Program in the 1970s and increased our understanding of how timber removal in a small watershed alters delivery of water, sediment, carbon, and nutrients to streams. Early stream ecology studies at HJA focused on detrital inputs from the forest and understory riparian vegetation (Anderson and Sedell 1979; Cummins 1974; Swanson et al. 1982a, 1982b; Triska et al. 1984). Since 1980, HJA researchers have participated in the National Science Foundation's Long Term Ecological Research (LTER) program, which has encouraged integrated ecosystem studies at multiple scales, ranging from small watersheds to regional river basins. The importance of large wood in streams, as geomorphic structures and habitat, emerged as an important theme at HJA in the mid-1970s and 1980s (Bisson 1987, Cummins 1980, Frear 1982, Harmon et al. 1986, Lienkaemper and Swanson 1987, Sedell et al. 1988, Sullivan et al. 1987, Swanson et al. 1976, Triska and Cromack 1980, Ward and Aumen 1986).

Research at HJA, throughout its history, has addressed management and policy concerns as well as basic science questions. For example, investigations at HJA of the ecological roles of riparian areas and large wood in streams and their importance for the health of stream habitats (Gregory et al. 1991) has provided a scientific basis to develop federal and state guidelines and regulations of forest management practices to protect water quality.

Availability of Publications and Data

Long-term data from reference and treated watersheds as well as from shorter term experiments, described below, are online at the HJA LTER Web page (Andrews Forest 2018). A bibliography of HJA publications is also available on that Web page. Long-term aquatic databases include stream chemistry (CF002, Johnson and Fredriksen 2017), chemistry of precipitation inputs (CP002, Johnson and Fredriksen 2016), NADP (CP001), stream temperature (HT004, Johnson and Gregory 2016) and streamflow (HF004, Johnson and Rothacher 2018). Data from the cross-site Lotic Intersite Nitrogen Experiment, phase II, are also online (AN006, Mulholland et al. 2015). HJA daily stream flow and meteorological datasets that are formatted for ready comparison with other experimental forests and ranges (EFRs) and LTER study sites are at the ClimDB/HydroDB website (LTER Network 2013).

Biological Responses to Stream Nutrients N and P

Issues of Concern

Western forest streams are sources of high-quality drinking water for downstream communities. They also support diverse aquatic communities that include amphibians and threatened and endangered fish species. Forested lands are not usually a source of excess nutrients in this region, but forest management can affect downstream water quality by altering streamflow, suspended sediment, nutrient concentrations, riparian forest conditions, and stream temperature. Land uses that are typical sources of excess stream nutrients, such as urban development, agriculture, and industry, are primarily located in large valleys downstream of forested headwaters. Where levels of stream nutrients are elevated, they can lead to eutrophication that can reduce the quality of drinking water and habitat for fish.

In the Pacific Northwest, many species of anadromous fish are declining and at risk of extinction. As a result, several species of anadromous salmon and trout (salmonids) have been listed as threatened or endangered under the Endangered Species Act. Causes of these species' decline include deterioration of critical habitat conditions in the region's rivers and streams. Several of these critical habitat features are related to water quality, including stream water temperature and sediment load. Streamside vegetation plays an important role in providing favorable habitat for these fish by providing shade, erosion control, and serving as a source of instream large wood. Measures to protect and restore habitat for these at-risk species have had economic and social impacts across the region.

Findings From Studies

Long-term data from forested reference watersheds and stream gaging stations—Studies of stream nutrients at HJA have been conducted for more than four decades. Researchers have examined the variability of nutrients as concentrations and fluxes at multiple temporal scales, ranging from within-storm to daily to seasonal to annual timesteps. Experimental additions of nitrogen (N) and phosphorus (P) have been used to examine the instream fate of nutrients as well as downstream export. Studies of multiple small watersheds have examined how timber harvest and regeneration influence nutrient dynamics and fluxes.

N and P dynamics in streams have been studied at the HJA since the 1960s. Researchers at HJA initially collected stream water for chemical analyses to address water quality concerns associated with forest harvest and to quantify fluxes of nutrient from these forests (Fredriksen 1969, Fredriksen and Moore

1972). Stream water concentrations in the western Cascade streams are very low in N and high in P, in contrast to Eastern U.S. streams, where N is abundant and P is scarce (Argerich et al. 2013, Likens et al. 1970, Martin and Harr 1988). By linking stream monitoring to management experiments, researchers were able to address questions about the role of decomposing litter and timber harvest as influences of instream nutrients.

In 1967, proportional sampling of HJA stream water (Fredriksen 1969) made it possible to have precise quantification of annual nutrient budgets and fluxes. Proportional samples from small gaged basins at HJA continue to be collected and analyzed for multiple chemical constituents (Argerich et al. 2013; Martin and Harr 1988, 1989; Vanderbilt et al. 2003). Datasets analysed in these studies are available (Johnson and Fredriksen 2016, 2017). Higher stream water concentration of many chemical constituents, including N and P, have been observed during high winter flows (Argerich et al. 2013, Fredriksen and Moore 1972, Hood et al. 2006, Martin and Harr 1988, Triska et al. 1984, Vanderbilt et al. 2003).

In HJA's undisturbed forest streams, inputs and outputs of N are primarily in organic form (Fredriksen and Moore 1972, Martin and Harr 1988, Vanderbilt et al. 2003). Inputs of N to HJA watersheds from precipitation are approximately 1 to 2 kg/ha/yr (Argerich et al. 2013, Fredriksen and Moore 1972, Martin and Harr 1988, Vanderbilt et al. 2003), or twice the flux of N in the stream outflow, suggesting retention of N within the forest and streams. The opposite has been found for P, where exports in stream water are twice the input from precipitation, likely owing to high concentrations of naturally occurring P in volcanically derived soils.

Average N concentrations in the small gaged watersheds at HJA range from 0.001 to 0.059 mg N/L for nitrate (NO_3^-) and 0.005 to 0.017 mg N/L for ammonium (NH_4^+). All the monitored watersheds have very low concentrations for NO_3^- , except WS 1 and Mack Creek, both of which show higher average NO_3^- concentrations (0.023 and 0.059 mg N/L, respectively).

Additional studies have examined the importance of riparian zones for stream functions (Gregory et al. 1991) and the role of large wood as channel structure and instream habitat (Swanson et al. 1982b). Stream biological communities have also been studied, including long-term monitoring of fish and salamander populations in Mack Creek since 1964 and studies of stream invertebrate species composition (e.g., Frady et al. 2007). Although stream nutrient concentrations have been monitored in HJA streams, response of stream communities to the low ambient nutrient conditions have not been examined.

Short-term studies of nutrient concentrations and export dynamics—

In an intensive study of a small watershed, Triska et al. (1984) quantified the sources of N being delivered to the stream in WS 10. They found that direct inputs of N in litterfall and lateral movement of leaf litter constituted 20 percent of the annual N inputs to streams, suggesting that the remainder of N inputs was associated with sub-surface flow and instream processes. Recent studies using tracers have investigated the multiple subsurface flowpaths of water that provide linkages between forests and streams. The median water residence time is influenced by the flowpath of the water as it moves through hillslopes (McGuire et al. 2005) and through hyporheic zones and returns to streams (Wondzell and Swanson 1996a). Residence time affects the uptake and transformation of N (Wondzell and Swanson 1996b).

Because concentrations of most cations and anions are influenced by fluctuations in streamflow, intensive sampling during storms has been important for examining the fine-scale timing of linkages between forests and streams (Hood et al. 2006, Johnson 2007). Higher concentrations of dissolved organic nitrogen (DON) and NO_3^- generally occurred during the rising limb of the hydrograph (fig. 5.2). Concentrations of DON (Fredriksen and Moore 1972) and dissolved carbon and NO_3^- (Sedell and Dahm 1990) tended to peak before the maximum of discharge. However, in watersheds with very low background concentrations of N, storms may only slightly increase the concentration of NO_3^- . Additional research has noted that as storms increase streamflows,

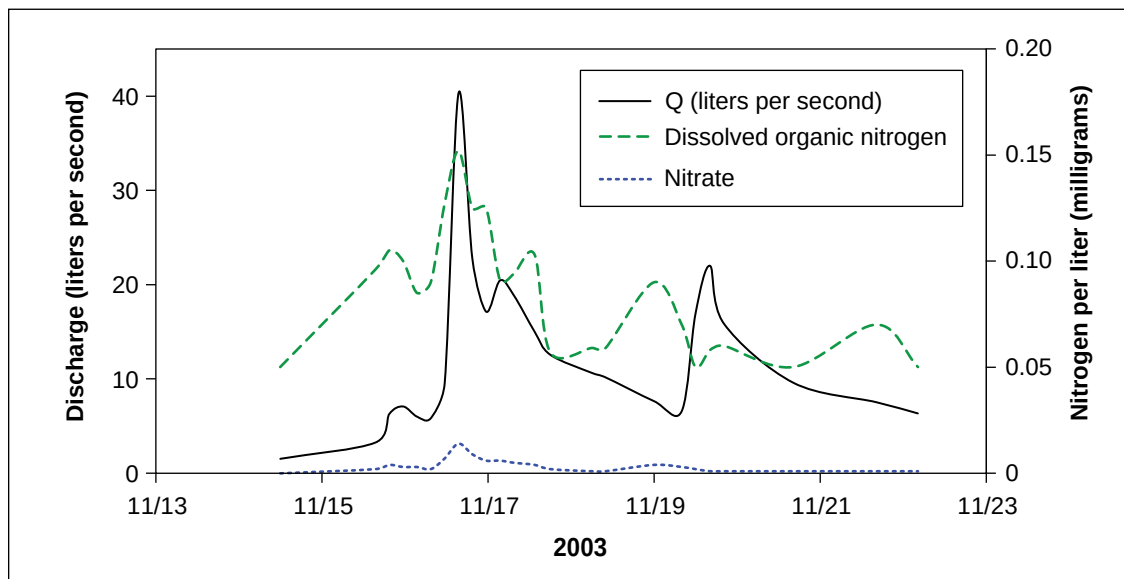


Figure 5.2—Concentrations of dissolved organic nitrogen and nitrate (NO_3^-) in watershed 2 during stormflow in November 2003 (Hood et al. 2004, Johnson 2007).

the form and concentration of nutrients entering streams often changes as different contributing areas within the watershed became hydraulically connected to streams (Hood et al. 2006; van Versveld et al. 2008, 2009).

Experimental studies of the fate and uptake of N and P in streams—

The transport, uptake, and fate of instream nutrients are influenced by biotic as well as hydrologic dynamics. These processes have been examined in multiple experimental studies at HJA. Instream experiments examining uptake of introduced NO_3^- have observed a range of uptake lengths; 17 m in a small stream reach with debris jams in WS 2 (Munn and Meyer 1990) and 900+ m in the larger Mack Creek (Sobota et al. 2012). Despite low concentrations of dissolved inorganic N in HJA streams, a multiyear release of ammonium nitrate (NH_4NO_3) into Lookout Creek found only limited responses in stream food webs.

Additions of ^{15}N isotope-labeled NO_3^- and NH_4^+ in Mack Creek revealed some of the complex flow paths of N within streams and across the terrestrial-aquatic interface. Researchers traced the fate of N as it was transformed, retained, or exported downstream. In Mack Creek, ^{15}N as NH_4^+ was added during summer 1998 and was added as NO_3^- during summer 2004. Within the 200-m study reach, approximately 50 percent of the labeled NH_4^+ was taken up or retained within the food web (Ashkenas et al. 2004), but only 15 percent of the labeled NO_3^- was retained (Sobota et al. 2012), indicating that NH_4^+ is much more bioavailable than NO_3^- . During both experiments, the dominant form of N being transported out of the reach was as NO_3^- , highlighting rapid rates of transformation of NH_4^+ to NO_3^- . Very little denitrification occurred in surface or subsurface environments (Sobota et al. 2012), likely a function of the well-oxygenated stream water even in subsurface environments.

To quantify rates of N uptake through the aquatic food web, the Lotic Intersite Nitrogen Experiments (LINXI) examined food web responses to a 42-day release of ^{15}N -labelled NH_4^+ . The primary producers or epilithon, consisting of algae, diatoms, mosses growing on rocks and instream wood, showed high uptake rates (table 5.2). Primary consumers, such as invertebrates and tailed frogs (*Ascaphus truei*) that scrape algae from rocks, became labelled with ^{15}N , as did predators, including cutthroat trout (*Oncorhynchus clarkii clarkii*) and coastal giant salamander (*Dicamptodon tenebrosus*) (Ashkenas et al. 2004). Increased ^{15}N values were also observed in riparian vegetation (Ashkenas et al. 2004), showing that stream water that infiltrated into the subsurface hyporheic zone transferred ^{15}N to the streamside vegetation.

Table 5.2—Comparison of the fate of ^{15}N tracer in Mack Creek, a third-order tributary of Lookout Creek, from isotope releases of ^{15}N -labeled NO_3^- -N (Sobota et al. 2012) and NH_4^+ -N (Ashkenas et al. 2004)

Fate of ^{15}N tracer (percentage)	$^{15}\text{NO}_3^-$	$^{15}\text{NH}_4^+$
In-reach detritus:		
FBOM	1	11
Leaves/needles	0	0
Wood biofilm and small wood	1	9
In-reach autotrophs:		
Epilithon	6	1
Aquatic bryophytes	7	9
Riparian plants	—	2
Aquatic biota	—	<1
Denitrification	<1	—
Export as NO_3^-	77	43
Export as NH_4^+	<1	2
Export as DON	—	4
Total percentage of tracer N	92	81

— = not reported

FBOM = fine benthic organic matter.

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

Riparian vegetation has been shown to have multiple influences on streams (Gregory et al. 1991). N-fixation associated with red alder results in increased N concentrations in streams (Hood et al. 2006, Vanderbilt et al. 2003). Litter inputs from riparian zones provide particulate N (Triska et al. 1984) and a source of food resources for stream invertebrates (Frady et al. 2007). Litter also influences the quality of carbon available (Yano et al. 2005), which has a role in regulating biological uptake of stream N. Shading from riparian vegetation influences stream temperature (Johnson 2004, Johnson and Jones 2000), which can also affect stream nutrient cycling and uptake processes.

Floodplains and associated hyporheic systems can be important locations for transformations of N (McClellan 1988; Wondzell and Swanson 1996a, 1996b). These studies demonstrate the functional relationships in small Cascade Range streams among instream large wood, flow through hyporheic zones and N processing in riparian zones. The structure and function of hyporheic systems changes in

response to channel dynamics in mountain streams (Kasahara and Wondzell 2003, Wondzell 2011, Wondzell and Swanson 1999). In narrow, steep, headwater streams, hyporheic flow commonly occurs through wedges of sediment lodged behind large wood in the channel. In the absence of large wood in steep channels, sediment can be flushed downstream and hyporheic flows reduced.

Dose-Response Studies

Except for the nutrient increase study by Gregory et al. (1991), systematic studies of the responses of stream biota to differing levels of nutrient enrichment have not been conducted at HJA. Therefore, we do not know in what ways long- or short-term increases in concentrations of N or P might affect stream biota and communities.

Reference Watersheds

Reference watersheds at HJA occur across a range of elevations and drainage areas (table 5.1) and are primarily dominated by old-growth Douglas-fir forests that originated after stand-replacing wildland fires centuries ago. Understory vegetation is diverse, including ferns, salal (*Gaultheria shallon* Pursh), huckleberry (*Vaccinium* spp.), and devil's club (*Oplopanax horridus* (Sm.) Miq.). Riparian overstory vegetation is dominated by bigleaf maple and western redcedar (*Thuja plicata* Donn ex D. Don). WS 2 and WS 9, at low elevations, have old-growth, Douglas-fir forests of age 500 years. WS 8, at mid elevation, has Douglas-fir forests of age 150 to 200 years. Mack Creek, a third-order stream, is surrounded by old-growth forest that is considered to be mostly undisturbed, although a few patches in the upper watershed were harvested in the 1970s. These reference watersheds are good representatives of old-growth forests in this elevation zone of the central Cascades of Oregon. Data from these watersheds have been used to represent the untreated condition in paired watershed experiments, and these watersheds have also been extensively studied in ecological investigations of the structure and function of old-growth forest and stream ecosystems.

Long-term monitoring of streamflow and stream water chemistry has been conducted at the outlets of HJA reference watersheds (see table 5.1). To investigate whether climate change or other exogenous factors might be changing the background concentrations of nutrients in undisturbed watersheds at HJA, long-term trends in reference stream nutrient concentrations were analyzed. Stream NO_3^- concentrations in WS 2 (1987–2007) and WS 8 and WS 9 (1972–2007) showed significant declines, but no significant trends were observed for Mack Creek (Argerich et al. 2013). NH_4^+ concentrations showed no trend in Mack Creek, WS 2, and WS 8, but increased over time in WS 9, which also showed decreases in streamflow (Argerich et al. 2013). Atmospheric deposition of N at HJA, which has remained low and stable (1978–2007) (Argerich et al. 2013; Kane et al. 2008; NADPa NADP 2017b), could not explain changes in stream water N concentrations.

Responses to Management and Natural Disturbances

The first study of stream nutrient responses to timber harvest at HJA began in 1962 in WS 1, WS 2, and WS 3 (Fredriksen 1971). These were followed by several additional experimental timber harvests in WS 6, WS 7 (Martin and Harr 1989), and WS 10 (Sollins and McCorison 1981) (table 5.1). Timber harvest of whole watersheds at HJA has been shown to lead to increased peak flows for the first 5 years postharvest (Jones and Grant 1996, 2001). Whole-basin clearcutting also resulted in short-term increased concentrations of NO_3^- (fig. 5.3), compared to preharvest levels or to reference watersheds (Sollins and McCorison 1981). Partial harvest showed limited responses (Martin and Harr 1989). However, even after whole-basin clearcutting, increases in NO_3^- concentrations were still very low relative to streams in other parts of the United States. The maximum postharvest stream NO_3^- levels at HJA never exceeded $0.5 \text{ mg NO}_3^- \text{ N/L}$, which is well below the federal drinking water standard for NO_3^- . However, in the nearby Calapooia watershed after debris flows and loss of alder canopy, Danehy et al. (2012) found substantial differences in NO_3^- in small streams. Timber harvest, followed by burning of slash in WS 1 resulted in little change in observed stream concentrations or fluxes of P (Martin and Harr 1989). There have been no studies at HJA of biological responses to possible postharvest changes in stream water nutrients.

Legacies of prior timber harvest on nutrient dynamics have been investigated using nutrient spiraling experiments. No clear continuing effects from earlier timber harvest were found in low-elevation or high-elevation gaged watersheds or in sections

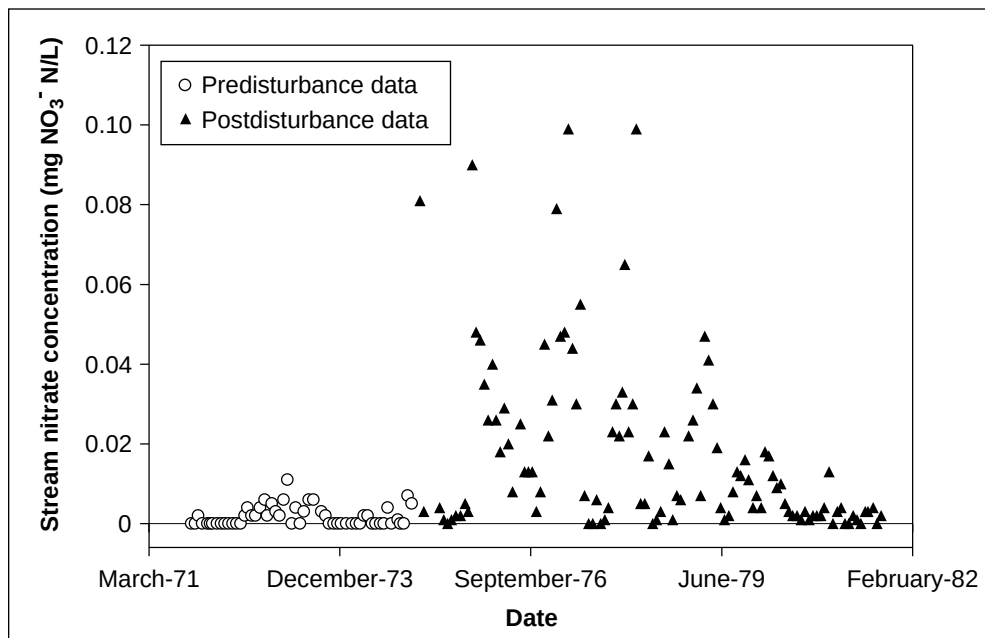


Figure 5.3—Stream nitrate-nitrogen ($\text{NO}_3\text{-N}$) concentration response to the logging and subsequent burning of watershed 6 during 1974–1975. (From: Johnson, and Fredriksen, 2016).

of clearcuts along Mack and McRae Creeks (Hill et al. 2010). Uptake distances for NH_4^+ averaged 94 m and ranged from 44 to 253 m across a range of flows.

Stream research at HJA has provided a scientific basis for developing numerous federal and state best management practices in Oregon and the Pacific Northwest. For example, research into responses of stream temperature to harvest (Levno and Rothacher 1967) and into structure and function of riparian zones at HJA (Gregory et al. 1991) served as a scientific basis for riparian buffer management guidelines for Willamette National Forest. This science was later used in developing the Northwest Forest Plan (FEMAT 1993), which set standards for management of riparian areas and streams on ~10 million ha of federal lands in Washington, western Oregon, and northern California as well as guidelines in this region for stream and riparian management in forests under state regulations (Ryan and Calhoun 2010). Long-term studies at HJA have found that natural disturbance events, including wildland fires, floods, and debris flows, have played formative roles in the structure and function of riparian areas and streams (Johnson et al. 2000, Swanson et al. 1998). Forest management designed to emulate natural disturbance regimes has drawn on HJA findings (Cissel et al. 1999).

Carbon Dynamics in Streams

The quantity and quality of stream carbon (C) also influence uptake of N and P. Streams and rivers process and transport C in multiple forms, ranging from dissolved organics and inorganic C to fine sediment and detritus to large logs. Research at HJA on stream C found that forested headwater streams can be significant exporters of C, both to the atmosphere and to downstream rivers (Argerich et al. 2016). Export of C from the stream occurs through downstream transport of dissolved inorganic carbon (63 kg C/ha/yr) and evasion of carbon dioxide (CO_2) from the stream surface to the atmosphere (42 kg C/ha/yr). The highest dissolved inorganic carbon and instream CO_2 concentrations occur during summer low flows, which coincides with maximum instream respiration rates. Downstream transport of organic C in dissolved and particulate forms averages 51 kg C/ha/yr. Most stream export of both dissolved and particulate forms occurs during winter high flows, indicating a seasonal lag between the peak CO_2 production and C export (Corson-Rikert 2014, Dosch 2014).

Cross-Site and Regional Studies

Synoptic concentrations of nutrients in HJA and broader stream networks—

Studies of forest-stream interactions throughout stream networks, from headwaters to large streams, emerged from several National Science Foundation-sponsored studies that developed from International Biological Program research. Scientists at HJA and three other sites led the development of the River Continuum Concept

(Vannote et al. 1980) based upon consistent, observed patterns of changes among multiple parameters across stream networks. They noted, for example, that as the riparian forest canopy opened with progressively wider channels, the food base for the stream organisms shifted from forest-derived organic matter to primary production originating within the stream in response to higher light levels.

To examine HJA stream nutrient concentrations in the context of the larger drainage basin, concentrations of N and P from multiple reaches across the Lookout Creek and larger McKenzie River basins were collected synoptically over 2

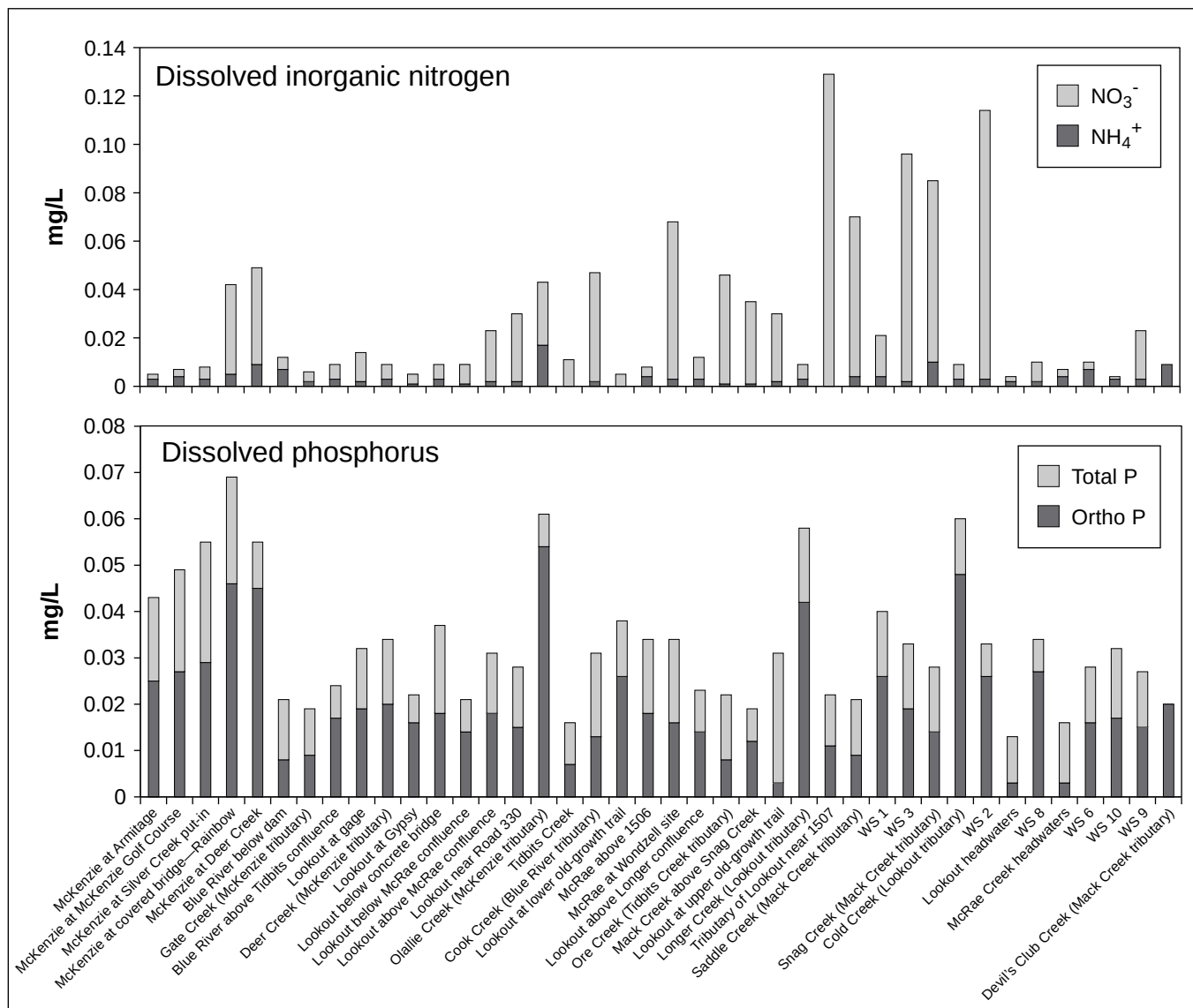


Figure 5.4—Concentrations of dissolved nitrogen (N) and phosphorus (P) during low flow, August 2000, in a range of sizes of streams at the H.J. Andrews Experimental Forest and McKenzie River basin. Sites are arrayed in descending order of upstream drainage area, from largest basin area (3000 km²) on the left, to smallest (0.002 km²) on the right. NH₄ = ammonium, NO₃ = nitrate, Ortho P = ortho phosphate-P, ws = watershed.

days during summer baseflow (fig. 5.4). The small headwater streams had very low concentrations, and the largest main channel also had very low concentrations owing to biological uptake, but in different stream compartments. In the headwaters, where the proportion of main channel water to subsurface water is low, biological uptake likely happens in the benthic and hyporheic biofilms, by heterotrophic bacteria. In the wide main channel of the McKenzie River, where light levels were high, primary producers were likely taking up N. Interestingly, the highest concentrations of dissolved inorganic N and variability in concentrations of N, especially NO_3^- , were observed in second-order streams. NO_3^- concentrations were much higher than NH_4^+ . One subbasin within HJA, Mack Creek, showed higher NO_3^- than other streams of similar size, possibly related to its soils and bedrock geology (Holloway et al. 1998). P concentrations were highest in streams with major contributions to their discharge from groundwater springs, especially in the headwaters and along the mainstem of the McKenzie River.

Lotic Intersite Nitrogen Experiments—

As part of a national cross-site experiment and synthesis, stream ecologists and aquatic biogeochemists collaborated to investigate the fate of N across a range of types of streams, including Mack Creek at HJA. In this cross-site experiment, called the Lotic Intersite Nitrogen Experiment (LINX I), the fate and rates of uptake of $^{15}\text{N-NH}_4^+$ tracer were studied throughout the stream and riparian food web at each of eight streams in different biomes. In 1998, researchers at HJA added $^{15}\text{N-NH}_4^+$ to Mack Creek for 42 days to track the movement of N from stream water into the aquatic and riparian biological systems (Ashkenas et al. 2004, Peterson et al. 2001). Building on these findings, a second cross-site experiment (LINX II) was organized to evaluate the fate of NO_3^- across a broader range of biomes and land use types (Mulholland et al. 2008, Sobota et al. 2012). These experiments released $^{15}\text{N-NO}_3^-$ for 24 hours at nine streams in each of eight regions for a total of 72 sites. Mack Creek was a site in both experiments. By using labeled isotopes of N, the LINX studies have contributed greatly to the understanding of N retention, transformation, and fluxes in streams (LINX Collaborators 2014). Data for LINX II studies are available online (Mulholland et al. 2015).

Comparison of Trends Over Time in Reference Watersheds

Long-term temporal trends in N chemical species in HJA streams were analyzed by Argerich et al. (2013) as a part of a cross-site synthesis effort from watersheds in the USFS experimental forest and range and LTER networks. The project, called StreamChemDB, compiled and analyzed standardized stream chemistry data from 72 forested watersheds within experimental forests and LTER sites across the United

States to inform stream nutrient criteria standards, analyze trends in N concentrations, and evaluate best sampling strategies and fluxes calculation methods for these small forested watersheds. The project created a stream chemistry database (Stream-ChemDB) with detailed documentation on stream chemistry analysis methods, sampling methods, and watershed history, which is available online (OSU 2017).

The temporal trends study evaluated time series of stream inorganic nitrogen concentrations from 22 forested reference catchments in seven experimental forests and LTERs spanning a wide range of climatic, hydrologic, and vegetation conditions across the United States. The study found that, although all sites were near-pristine forested streams, NO_3^- concentrations showed a wide range of values from 0.001 mg N/L at HJA to 0.753 mg N/L at Fernow Experimental Forest in West Virginia. Stream NO_3^- decreased over time at HJA, in the Pacific Northwest, as well as in the Northeast, and Puerto Rico, and increased in the mountain West and the South (Argerich et al. 2013). Other key findings included that detection and direction of trends in reference watersheds differed with the length of record of data analyzed and that adjacent reference watersheds within a site did not necessarily show similar patterns over time.

Reliability and Limitations of Findings

Data quality at HJA is high and consistent over time. Documentation of the analytical methods and detection levels are available on the Cooperative Chemical Analytical Lab Web page (OSU 2018). Metadata for sample handling protocols are online with each of the databases.

Research results and monitoring datasets from HJA are probably applicable to other forested headwater streams in the western Cascades. However, where the geographic setting, geologic history, or land use differ from HJA's, or a high degree of accuracy is required, we recommend considering validation studies or monitoring to test how well the results from HJA apply to other conditions.

Research Needs

The highest priority research question relevant to state and federal water quality regulation that could be addressed at the HJA is, What are the relationships between nutrient levels and biological communities, including algal, macroinvertebrate, and vertebrate species, in reference streams with minimal human disturbance? This question is important because healthy aquatic communities are a designated beneficial use of surface waters regulated under the Clean Water Act. The establishment of baseline conditions is critical to properly assess the effects of pollutants on sensitive aquatic communities. Future research that would be needed to investigate responses of stream biological communities to nutrients at the HJA includes

surveys of additional reference stream biological communities and experimental stream nutrient additions designed to look at changes in biological communities in response to different levels and combinations of chronic and pulsed nutrient enrichment. Linking changes in biological communities to water quality parameters regulated under Oregon's water quality standards, including pH, dissolved oxygen, and chlorophyll *a*, would also be important, as numeric standards for these parameters are most commonly used for deriving permit limits and developing total maximum daily loads.

Potential Utility to Water Quality Regulatory Agencies

Information from research on stream nutrients and existing long-term stream nutrient data from HJA might be useful in determining concentrations of N and P and relationships between nutrients and biological communities (algae and macro-invertebrates) in streams under reference conditions in forested watersheds. This information might be used as inputs in watershed models that identify whether nutrients may contribute to water quality impairments, as well as for determining the sources of those nutrients. The application of the research from HJA would likely be limited to headwater streams of forested watersheds in the western Cascades. Such a limitation is due to the generally lower N concentrations in HJA streams compared to forested coastal watersheds, which often have higher N associated with red alder and substrate type (Compton et al. 2003). Streams in the drier forested areas east of the Cascades also tend to have higher N concentrations (Wise and Johnson 2011). Existing long-term data on P concentrations at HJA would likely be of utility for setting baselines in P-rich parts of western Oregon and Washington, such as areas with basaltic geologies or that have received inputs of volcanic ash. Studies of export of dissolved and particulate C in forested streams at HJA might be useful to regulatory agencies for developing appropriate management guidelines for controlling dissolved and particulate C export from forested watersheds that act as drinking water sources.

Key points:

- Long-term, year-round data from forested reference and treated watersheds at HJA are valuable for understanding responses to short-term disturbances or changing climate.
- In general, streams in the Cascade Mountains are low in N but have abundant P.
- Research on processes of uptake and the fate of sequestered N has shown the importance of maintaining habitat complexity in streams and riparian areas.

- Timber harvest or disturbances can produce short-term, seasonal increases in NO_3^- concentrations for up to several years after the disturbance.
- Existing HJA science findings and datasets might be used by regulatory agencies to develop watershed models that identify whether nutrients may contribute to water quality impairments, as well as for determining the sources of those nutrients.
- Future studies at HJA that would fill the highest priority science need of the regulatory community would be investigations of the relationships between nutrient levels and biological communities including algal, macroinvertebrate, and vertebrate species in reference streams with minimal human disturbance.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

There are currently no issues of concern related to stream nutrients other than N and P in this region.

Findings From Studies

Long-term monitoring of major chemical anions and cations that has been conducted in HJA streams (Johnson and Fredriksen 2017) and precipitation water (Johnson and Fredriksen 2016) has included silicon dioxide, sodium, potassium, calcium, magnesium, sulfate, and chloride. Additional stream water constituents analyzed have included dissolved organic carbon, pH, suspended sediment, alkalinity, and specific conductivity. Stream and air temperature are measured onsite at each stream gage (Johnson and Gregory 2016). Limited analyses of these additional cation and anion data have shown regular and repeated seasonal patterns (Martin and Harr 1988).

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

Factors measured at HJA that would affect biological responses to N and P, discussed earlier, would also affect responses to nutrients other than N and P.

Dose-Response Studies

Dose-response to nutrients other than N and P has not been studied at HJA.

Reference Watersheds

The streams that drain HJA reference watersheds have been monitored for nutrients other than N and P. These data show regular seasonal patterns (Martin and Harr 1988), but otherwise they have been relatively little studied.

Cross-Site and Regional Studies

Datasets on nutrients other than N and P from HJA have not been included in cross-site or regional studies.

Responses to Management and Natural Disturbances

Although streams at HJA that drain watersheds that received forest management treatments have been monitored for nutrients other than N and P, effects of these treatments on these stream nutrients have not been studied in detail.

Reliability and Limitations of Findings

Research results and monitoring datasets from HJA are likely applicable to other forested headwater streams in the western Cascades. However, where the geographic setting, geologic history, or land use differ from HJA or a high degree of accuracy is required, we recommend considering validation studies or monitoring to test how well the results from HJA transfer to other conditions.

Research Needs

No research needs related to nutrients other than N and P that are of interest to regulatory agencies were identified at HJA.

Potential Utility to Water Quality Regulatory Agencies

Because nutrients other than N, P, and C are not currently of concern in this region, HJA findings and datasets on these nutrients are probably not of immediate use to regulatory agencies. If issues related to these nutrients were to arise in the future, these HJA data would be available for use.

Key points:

- Nutrients other than N and P have been monitored in stream water, precipitation, and atmospheric deposition at HJA.
- There are currently no regional issues related to these nutrients in stream water, and there has been relatively little research related to them at HJA.

Overview and Synthesis

HJA is a forested watershed in the Cascades where streams in both undisturbed and managed conifer forests have been studied indepth. The many years of study of stream chemistry at HJA allow researchers and managers to better understand the natural variability of stream nutrients in response to year-to-year conditions and natural and anthropogenic disturbances. The continuous monitoring of both stream nutrients and streamflow allows annual budgets and fluxes to be accurately calculated. These streams are N limited and have abundant P, as do many streams in volcanic areas of the Northwest.

Tracer experiments have shown the importance of hydraulic flow paths on N processing and uptake within streams, and the role of stream biofilms, microbes, and primary producers in sequestering N from the water column and from subsurface hyporheic zones. These intensive tracer experiments are very useful for understanding processes that influence instream availability of nutrients and suggest that restoration and maintenance of diversity of instream habitat might be potentially important to help mitigate high nutrient levels.

Experiments at HJA that have explored ecological processes can potentially be applied to broader areas than just the ecoregion under study. Better understanding of biological responses to a gradient of nutrients would be useful to water quality regulators as they work to set thresholds and nutrient criteria. These types of experiments would have to consider multiple trophic levels and hydraulic flow paths; the interactions of streamflow, stream biota, and water temperature; and shifts in nutrient limitation and colimitation as nutrient availability is changed.

Key points:

- Long-term, high-quality, well-documented data from HJA are openly available online and being used to inform nutrient criteria across regions.
- HJA researchers have been investigating the processes that influence availability, fate, and uptake of stream nutrients.
- Better understanding of natural variability in nutrients and biological responses to them under reference stream conditions might be useful for regulatory agencies to develop baseline water quality criteria.

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Chapter 6: Ecoregion 6.2.10 Middle Rockies: Tenderfoot Creek Experimental Forest, Montana

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Introduction

This chapter is a review and synthesis of research conducted at Tenderfoot Creek Experimental Forest (TCEF) on biological responses to stream nutrients. It is intended to inform national and regional water quality regulatory agencies, such as the U.S. Environmental Protection Agency and the Montana Department of Environmental Quality (DEQ), about existing results of relevant scientific studies that are available at TCEF, and to identify future field and synthetic research of potential use to regulatory agencies that might be conducted at TCEF.

Site Description

TCEF (lat. 46° 55' N, long. 110° 55' W) is in the Little Belt Mountains, within the Lewis and Clark National Forest in central Montana. Tenderfoot Creek drains this third-order watershed, 22.8 km² in total area, comprising eight first- or second-order subwatersheds ranging in size from 3 to 22.8 km² (fig. 6.1) (Jencso et al. 2009). Topography is mountainous and ranges in elevation from 1840 to 2420 m (Pacific et al. 2009).

The streams in the Tenderfoot Creek watershed are headwaters of the Smith River, a tributary of the Missouri River. Streams at TCEF have a moderate gradient of approximately 2 to 4 percent, and typically have a series of small pool-riffle sequences. The streams are Rosgen type B with moderately sinuous channels and limited floodplain development because of the constrained valley geomorphology (Rosgen 1996). Streambed substrate is a mix of coarse gravels and small rocks, cobbles, and sand. Riparian corridors are predominately vegetated by a mix of grasses, sedges, and willow species. The lack of large trees in riparian zones results in very little large woody debris in these streams.

Total stream length varies seasonally, as channel extent and discharge are strongly controlled by watershed wetness. During wet periods, such as snowmelt, the stream network expands farther into headwater reaches and streams widen, often into riparian areas. During dry periods, the network shrinks, and flow is contained

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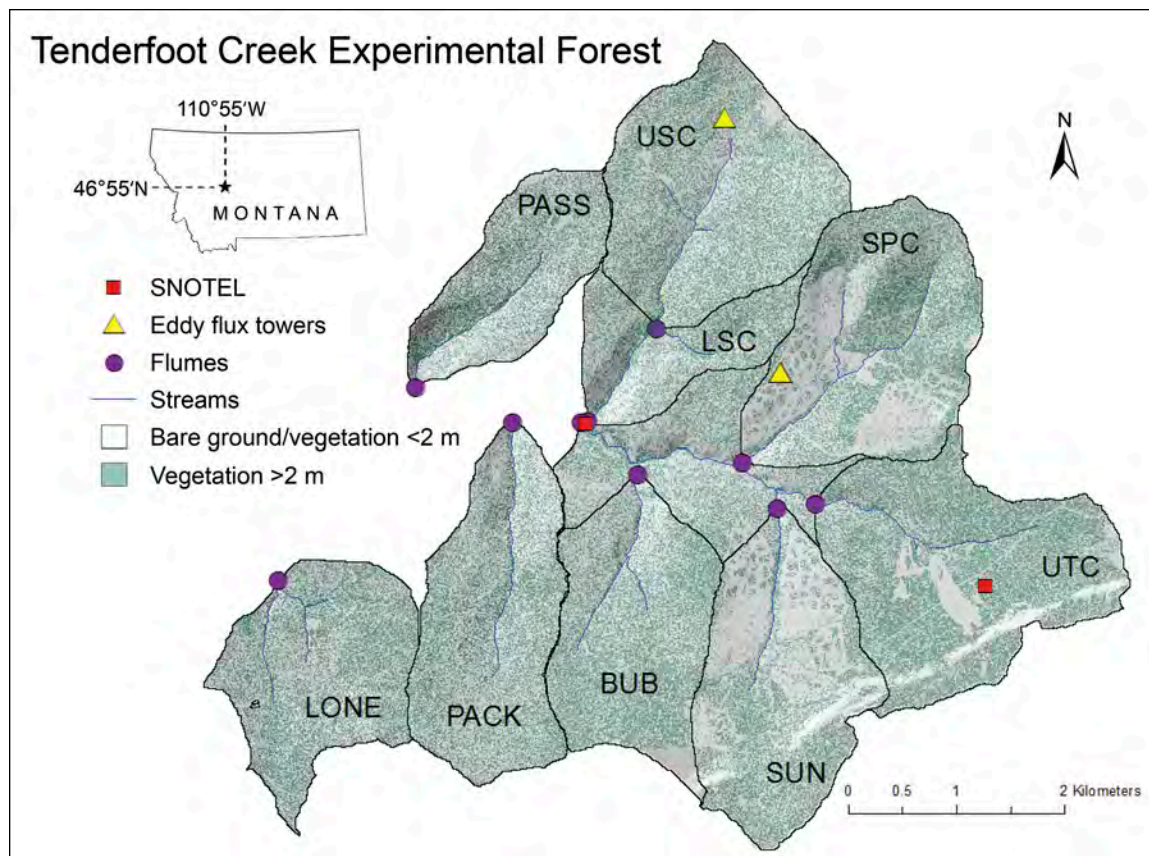


Figure 6.1—Tenderfoot Creek Experimental Forest. Locations of snow telemetry (SNOTEL), eddy flux towers, and flume gaging stations are shown against the vegetation coverage. Following are eight subwatersheds that are monitored with stream gages: Passion Creek (PASS), Upper and Lower Stringer Creek (USC and LSC, respectively), Spring Park Creek (SPC), Upper Tenderfoot Creek (UTC), Sun Creek (SUN), Bubbling Creek (BUB), Pack Creek (PACK), and Lonesome Creek (LONE).

in the primary stream channel. Baseflow is predominately fed by shallow groundwater and saturated zones within riparian areas as well as by lateral redistribution of unsaturated soil water. Headwater streams at TCEF are an important source of water that sustains downstream habitat, such as invertebrate drift, which is a food source for rainbow trout (*Oncorhynchus mykiss* Walbaum) and brown trout (*Salmo trutta* L.) populations in lower Tenderfoot Creek and the Smith River (Wipfli et al. 2007).

Bedrock geology is predominantly igneous sills of quartz porphyry, Wolsey shales, Flathead quartzite, and granitic gneiss (Mincemoyer and Birdsall 2006). The dominant soil types found in the watershed are loamy, skeletal, mixed Typic Cryochrepts and clayey, mixed Aquic Cryoboralfs (Mincemoyer and Birdsall 2006).

Climate is continental with a mean annual temperature of 0 °C. Freezing temperatures can occur every month of the year, producing an average frost-free season of 30 to 45 days on ridges and 45 to 75 days at lower elevations (Mincemoyer and Birdsall 2006). Mean annual precipitation is 880 mm, and ranges from 594 to 1050 mm from low to high elevations, respectively (Mincemoyer and

Birdsall 2006, Pacific et al. 2009). Seventy percent of precipitation falls as snow between the months of November and May. Peak runoff occurs following snowmelt in late May and early June (Nippgen et al. 2011). Precipitation is uncommon in mid to late summer, producing strong temporal gradients of decreasing wetness and increasing air and water temperature from the end of snowmelt until late summer.

Vegetation is predominantly lodgepole pine (*Pinus contorta* Douglas ex Loudon) forest, on ~65 percent of the watershed area, with a shrub layer composed primarily of *Vaccinium scoparium* (Leiberg ex Coville) (Ahl et al. 2008). Interspersed patches of spruce-fir (*Picea engelmannii* (Parry ex Engelm.) and *Abies lasiocarpa* (Hook.) Nutt.) forest occur on ~20 percent of the watershed area, and floristically rich wet meadow complexes and open grassy slopes composed principally of *Deschampsia cespitosa* (L.) P. Beauv., *Carex* spp., and *Festuca idahoensis* (Elmer) occupy ~5 percent (Mincemoyer and Birdsall 2006). For several centuries prior to establishment of TCEF, these forests experienced periodic, low-severity burns that thinned understory vegetation and reduced standing stocks of coarse woody debris.

Research History

TCEF was established in 1961 with a mandate to investigate forest harvesting techniques that could promote soil stability in lodgepole pine ecosystems, while simultaneously increasing water yields (USDA FS 2017b). Little research was conducted until the late 1980s, when the research mandate was widened to include investigation of the fire history and other ecological, biological, and physical processes that could better inform the practice of landscape-level management.

In 1991, the Tenderfoot Research Project (TRP) was established for the purpose of evaluating the effectiveness of large-scale, ecosystem-level silvicultural treatments that mimic natural disturbance effects. From 1999 to 2001, a comprehensive silvicultural experimental treatment was implemented in Spring Park Creek and Sun Creek subwatersheds. Shelterwood-with-reserve harvests were conducted in 16 units that removed 50 percent of the total basal area and left residual trees in two configurations: either evenly spaced or grouped in patches of residual trees separated by clearcut corridors (Baker et al., n.d.; Woods et al. 2006). These treatments were intended to mimic dual-aged stands in natural lodgepole pine forests.

Since 2004, researchers from Montana State University and other institutions have cooperated with the U.S. Forest Service (USFS) to conduct watershed-level hydrologic research, and later installed two eddy-covariance flux towers, and distributed soil moisture sensors and shallow groundwater well transects in many of the subwatersheds. Since then, research at TCEF has investigated the interacting influences of landscape complexity and climate variability on streamflow generation, biogeochemical processes, solute export, and land-atmosphere trace gas, water, and energy balances.

Availability of publications and data—

Publication citations and an annotated bibliography of most of the research conducted at TCEF is available on the TCEF website (USDA FS 2014). Other data available through the USFS Research Archive (USDA FS 2017a) includes 15-minute streamflow data, annual precipitation, fluvial sediment transport data, and water quality data on semiannual timescale. Long-term daily streamflow and meteorology data, formatted for ready comparison with other experimental forest and range and Long-Term Ecological Research Network sites, may be downloaded at the ClimDB/HydroDB website (LTER Network 2013). Additional datasets may be available by contacting individual scientists or research project principal investigators.

Biological Responses to Stream Nutrients N and P**Issues of Concern**

Nitrogen (N) and phosphorous (P) enrichment can arise from a variety of natural and anthropogenic causes, such as atmospheric deposition, agricultural fertilizer application, surface runoff and septic system discharges from development at the urban-wildland interface, and increased nutrient runoff after timber extraction (Foley et al. 2005, Vitousek et al. 1997). Nutrient enrichment of surface waters in this region can lead to eutrophication, which can degrade the quality of water for beneficial uses, such as drinking water; habitat for aquatic organisms, especially fish; and water recreation such as fishing, rafting, and swimming (Smith 2003). Fish populations are especially vulnerable to eutrophication because it leads to decreased dissolved oxygen levels in the water column. Many recreationally valuable fish species require well-oxygenated water to survive. Downstream of TCEF, the Smith River hosts a nationally renowned trout fishery that has great recreational and economic value to the state of Montana (Montana Fish, Wildlife and Parks 2009) but might be vulnerable if water quality were degraded.

Many streams at TCEF and in the surrounding area have low ambient nutrient concentrations that might make them sensitive to changes in nutrient enrichment from changes in land use, land cover, or atmospheric deposition. Studies at TCEF, which are representative of forested headwater basins in the region, can inform regulators' understanding of undisturbed stream ecosystem function and might also help them consider how oligotrophic, topographically complex watersheds in this region may respond to changes in climate and land use.

Findings From Studies

To date, Tenderfoot Creek has remained completely undeveloped and is in a region with low nitrogen wet deposition rates (<2.0 kg N/ha/yr) (NADP 2019). Forestry practices have been small scale and controlled, with most of the subwatersheds remaining undisturbed. Thus N and P enrichment has not yet been a concern in this system, and streams remain highly oligotrophic.

Because TCEF remains largely undisturbed biogeochemically, there are no published studies specifically examining the response of the biotic community at TCEF to N and P enrichment. Studies have primarily focused on understanding how watersheds translate rainfall and snowmelt into runoff and on investigating the influence of complex topography and climate variability on streamflow, solute export, and atmosphere-land exchange. The USFS has monitored major cation and anion concentrations in stream water at the outlet of all subwatersheds at TCEF approximately biannually from 1992 to 2009 and from 2014 to present. Mean annual stream water concentrations of N (10 to 20 $\mu\text{g NO}_3^-$ -N/L) and P (30 to 40 $\mu\text{g PO}_4^{3-}$ -P/L) have been generally low, as is typical in relatively undisturbed headwaters in this region (McCaughey et al. 2010). High temporal frequency, in situ sensors, deployed in 2013 by the authors, revealed the complex nature of stream solute dynamics, including diel concentration swings and snowmelt pulses within observed seasonal and annual patterns not captured previously by biannual or quarterly grab sampling.

Research by the authors is currently underway at TCEF to better understand how streams cycle N and how they may respond to N enrichment. Seybold and McGlynn (2018) are exploring seasonal changes in stream N retention and export in response to hydrologic drivers and carbon substrate availability, and how instream N processing may be coupled to rates of stream metabolism. These studies will provide experimental insight into N uptake kinetics at concentrations ranging from ambient levels to saturation concentrations in several study streams at TCEF, which could provide a baseline for understanding how the system will respond when perturbed by both short-term acute and chronic low-level N enrichment. No studies have been conducted at TCEF on responses of organisms and stream communities to nutrients, or on surveys of upper trophic levels.

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

Landscape hydrodynamics—

The wealth of hydrologic research conducted at TCEF has important implications for how streams may respond to N and P enrichment. Work conducted at TCEF has demonstrated the dominant role of landscape structure in mediating runoff generation processes and hydrologic connectivity between streams and hillslopes.

Solute delivery from the terrestrial landscape is a primary control on instream nutrient enrichment. Mechanisms that deliver N and P from the surrounding watershed differ spatially and temporally, which has important implications for when and where enrichment occurs and whether the biotic community has the capacity to respond to, or partially mitigate, increased nutrient loading.

Several studies by Jensco et al. (2009, 2010) and Jensco and McGlynn (2011) demonstrated the important role of landscape structure in mediating hillslope

hydrologic connectivity. Simple metrics such as the size of the upslope contributing area, or upslope accumulated area (UAA), can explain the extent of hillslope-riparian-stream (HRS) connectivity in a watershed. Watersheds that have a high proportion of large UAA hillslopes exhibit higher levels of HRS hydrologic connectivity, and supply a more constant flux of terrestrial solutes from hillslopes to streams than do topographically complex watersheds with a smaller proportion of large UAA hillslopes (Smith et al. 2013).

Riparian areas are also a contributing source of solutes, particularly dissolved organic carbon (DOC), to the stream ecosystem throughout the snowmelt and base-flow period (Pacific et al. 2010). They act as important nutrient sinks and as hotspots of active biogeochemical processing that can remove excess nutrients from soil and shallow groundwater via anaerobic metabolic processes and physical sorption in sediments (Hill 1996). Thus the frequency with which water stored in riparian areas is fully replaced has implications for how frequently riparian solutes are flushed into the stream and, conversely, the extent to which riparian areas can effectively buffer stream concentrations from terrestrial inputs. These findings are consistent with the concept that healthy riparian areas are critical for protecting stream functions that underly many riparian best management practices and guidelines.

Jensco et al. (2009, 2010) demonstrated that riparian buffering capacity and riparian zone turnover time is controlled by the ratio of hillslope area to riparian zone area. For example, a large hillslope that drains to a narrow riparian area will lead to short riparian turnover times and a limited capacity for the riparian zone to buffer the stream from terrestrial inputs. In contrast, riparian areas with long turnover times are able to effectively buffer the stream by dampening the magnitude of the input and by prolonging the duration of the response. In several riparian zones at TCEF, Jensco et al. (2010) concluded that full turnover of riparian soil water can take up to 2 years or more in some locations. This finding implies that in some watersheds, there may be a sizeable timelag between changes in terrestrial loading and subsequent changes in stream concentrations. In these types of watersheds, stream concentrations might not respond immediately to best management practices that decrease nutrient loading within the watershed because of inertia created by riparian buffering. These studies illustrate the important control that landscape structure exerts on the sources, quantity, and timing of water and solute delivery from the terrestrial landscape to the stream channel (Jensco et al. 2009, 2010; Jensco and McGlynn 2011).

Climate variability is another important driver of terrestrial hydrodynamics and solute loading. A study from TCEF by Nippgen et al. (2011) found that interwatershed variation in topographic indices, which are metrics of the average amount of time it takes for a precipitation input to be translated into a runoff output, explained

the variability in mean response time of watersheds at TCEF. Runoff ratios within a given catchment were strongly correlated with topographic indices describing the watershed's structure, such as the degree of convergence, distance from creek, gradient to creek, convergent area, and riparian buffering capacity. Runoff ratios for individual basins do not reflect larger scale climate metrics, such as maximum snow-water equivalent (SWE). In contrast, climate variability was an important driving factor in controlling intrawatershed variability in runoff.

Annual variation in SWE was correlated to the annual variation in mean response time within a given watershed. For example, years with high SWE had the fastest mean response times, whereas years with low SWE had the slowest response times. This indicates that both landscape structure and climate forcing are important first-order controls on runoff generation and solute loading, but that these drivers operate over different spatial and temporal scales.

Land-atmosphere interactions—

Topographic-driven water redistribution affects solute export from the terrestrial ecosystem, and also exerts a strong control on the generation of solutes via soil biogeochemical processes. For example, soil carbon dioxide (CO₂) efflux is a product of aerobic soil respiration and mineralization of organic matter, and thus can be viewed as an indicator of soil biological processes. While not a direct measure of nutrient cycling in soils, landscape-level variation in CO₂ fluxes can indicate locations and periods of active nutrient cycling and microbial decomposition.

Extensive work by Pacific et al. (2008, 2009, 2011), Riveros-Iregui et al. (2011, 2012), Riveros-Iregui and McGlynn (2009), and Emanuel et al. (2011) investigated the central role of landscape complexity in determining the spatial and interannual variability of soil CO₂ fluxes. In studies of Stringer Creek subwatershed (fig. 6.1), the highest soil CO₂ fluxes were observed in riparian sites with consistently high soil moisture and high UAA values (Riveros-Iregui and McGlynn 2009). Hillslope positions with low soil moisture and low UAA values were characterized by low soil CO₂ flux rates. Soil CO₂ concentrations were correspondingly higher in the riparian zones than in the hillslopes and correlated with higher soil water content (Pacific et al. 2008). Cumulative soil CO₂ fluxes across the growing season were highest in riparian areas with high UAA and gentle slopes, where groundwater tables were present throughout the entire growing season (Pacific et al. 2011). These findings were evidence that topographically driven water redistribution, and subsequent soil water availability, is an important driver of the spatial patterns of soil microbial processes within the landscape.

Climate forcing, expressed as interannual variation in water availability, can also explain temporal trends in soil CO₂ fluxes. In lowlands and riparian areas with

high UAA values, cumulative soil respiration was 24 percent lower in wet years than dry years (Pacific et al. 2009, Riveros-Iregui et al. 2012). In contrast, hillslope positions with low UAA values exhibited higher soil respiration in wet years compared to dry years. This bidirectional behavior of soil respiration in response to a single climatic or hydrologic forcing suggests that under a wetter climate some portions of the watershed became a stronger carbon source, while other portions of the watershed became a weaker source. This bidirectional behavior probably produced a more muted response to climate variability from the watershed as a whole (Pacific et al. 2009, Riveros-Iregui et al. 2012).

Instream dynamics—

Landscape structure and groundwater-surface water exchange are both important drivers of instream solute concentrations and watershed fluxes, and the interaction of these drivers creates spatial and temporal variation in solute dynamics at the watershed scale. Dissolved organic carbon dynamics in aquatic systems are tightly coupled to the terrestrial watershed (Ågren et al. 2014, Boyer et al. 1997, Hood et al. 2006, McGlynn and McDonnell 2003, Pacific et al. 2010). In most oligotrophic watersheds, terrestrial carbon is an important subsidy of energy into stream ecosystems and also an important, and largely unaccounted for, component of the overall carbon balance of watersheds (Cole et al. 2007, Pacific et al. 2010). Thus, understanding the controls on both land-atmosphere and land-stream carbon export is important for assessing the role of streams in the watershed carbon balance.

Pacific et al. (2010) demonstrated that variation in DOC concentrations in streams at TCEF was largely driven by the spatiotemporal intersection of HRS connectivity and activation of carbon-rich source areas within the landscape (Pacific et al. 2010). Both HRS and variable-source activation were important controls on instream DOC concentrations, and the greatest export occurred when both were maximized. Variation in these two controls also explained interwatershed variation in DOC export across the experimental forest.

Groundwater-surface water interactions add another layer of complexity to the spatial and temporal variation in stream solutes dynamics. In a study of Stringer Creek, Payn et al. (2009) found a wide range of multiscaled hyporheic flowpaths that were characterized by a broad distribution of transport times and flowpath lengths. These multiscaled flowpaths resulted in both groundwater recharge and discharge into the channel over a single reach. Thus, net changes in stream discharge were a combination of both gains and losses of water and solutes from and to the groundwater system. Because streams are continuously exchanging water with groundwater, this interaction may provide resistance to rapid changes in stream solute concentrations and act as a short-term buffer to concentration changes.

The research at TCEF clearly demonstrates that hillslope dynamics, landscape structure, and resulting groundwater dynamics can play a critical role in controlling solute export and the spatiotemporal variation in stream concentrations. Studies from TCEF by Seybold and McGlynn (2017) also found that instream ecological functions, such as metabolic processes and nutrient cycling, are tied to hydrodynamics at the watershed scale. For example, in a study in two adjacent first-order subwatersheds of Tenderfoot Creek, Seybold and McGlynn (2017) found that seasonal patterns in ecosystem metabolism were correlated with the degree of hydrologic connectivity in the watershed, and also that interwatershed variation in hydrologic connectivity drives differences in the amount of carbon respired by streams. This preliminary study suggested that stream ecosystem function was tightly coupled to nutrient and water fluxes from the terrestrial watershed.

Reference Watersheds

Three subwatersheds within TCEF can serve as *de facto* reference watersheds that represent undisturbed forest conditions in this region. Stringer Creek (550 ha), Upper Tenderfoot Creek (446 ha), and Bubbling Creek (309 ha) have remained undisturbed since TCEF's establishment in 1961 and have had no silvicultural experiments within their boundaries. Prior to the formation of TCEF, these watersheds were never harvested for timber, cleared for settlement or otherwise developed, and are only minimally affected by low levels of atmospheric deposition. These watersheds may serve as a reference for stream biogeochemical function as well as stream biological communities in undisturbed watersheds. The USFS has monitored N and P concentrations in these streams biannually since 1992, although no studies or monitoring of aquatic organisms have been conducted in these systems. Undisturbed, instrumented watersheds with long-term data records are rare and of potentially great value to the regulatory community for establishing baseline conditions. TCEF could serve as a high-value reference site for high-elevation, forested catchments.

Although watersheds at TCEF have been minimally disturbed to date, the USFS charter for TCEF does not officially designate that these sites be maintained as reference watersheds. The charter allows for timber harvesting associated with research activities, so some sites currently functioning as potential regulatory reference sites might have trees cut or be otherwise manipulated for research in the future. In that case, their streams might no longer meet the strictest Montana DEQ reference benchmark (Tier 1: natural condition), but, depending on the degree of disturbance to plants and soils, might qualify as Tier 2 reference sites with minimally affected conditions (Suplee et al. 2005). If the USFS revised the TCEF charter

to designate one or more subwatersheds to remain permanently with minimal onsite human disturbance, it would assure that benchmark reference streams for regulatory purposes would be maintained into the future. In addition, establishing reference basins at TCEF would enhance the scientific value of future studies at this site by providing a reliable internal reference, against which long-term effects on streams of experimental treatments could be compared.

Dose-Response Studies

No dose-response studies have been conducted at TCEF.

Cross-Site and Regional Studies

To date, TCEF has not been included in any cross-site studies or syntheses related to nutrients owing to the limited amount of work conducted there on N and P cycling in streams. TCEF has been included in a continental-scale hydrologic meta-analysis that investigated the effects of climate change on streamflow across ecosystem types in the United States (Jones et al. 2012). Comparing effects of climate change on streamflow across different ecosystems, they found that long-term streamflow records were correlated with large-scale climate indices, such as El Niño, Pacific Decadal Oscillation, and North Atlantic Oscillation, during periods of the year when the influence of vegetation was minimal. This suggested that at TCEF, the amount of snowfall and subsequent snowmelt runoff in the spring, while vegetation is relatively inactive, would be more strongly correlated with larger scale climate patterns than with local controls. This finding is consistent with the report by Nippgen et al. (2011) that climate variability was a strong driver of interannual variation in runoff at TCEF.

Responses to Management and Natural Disturbances

Timber harvesting and silvicultural practices—

Land use changes and management strongly interact with runoff generation mechanisms to influence patterns of solute loading. In a study at TCEF, Woods et al. (2006) found strong evidence that the spatial configuration of timber harvest areas influenced the amount of snow accumulation in the remaining stands, and thus the amount of water stored in the landscape to generate runoff. Stands with evenly spaced residual trees accumulated more snow than residual trees left in dense patches. Even spacing decreased snow interception and ablation and increased snowpack by up to 35 percent over the untreated control stands. These findings indicate that decisions about the details of timber harvest practices, such as the pattern of residual trees, may have important implications for how much runoff is generated during snowmelt. Harvesting effects probably combine with geomorphic structure of the watershed

to determine which parts of the landscape are activated and contribute water and solutes, including dissolved N and P, to the stream ecosystem.

Timber harvesting can also significantly affect suspended sediment (SS) dynamics of a watershed (Grant and Wolff 1991). Stream SS concentrations have important ramifications for biotic communities, including salmonid fish. Elevated turbidity can alter the underwater intensity and spectral distribution of light, which in turn influences primary productivity, photodegradation of organic matter, water temperature, and visual cues for aquatic organisms (Julian et al. 2008). Thus understanding the drivers of sediment export from watersheds is critically important for predicting when and where biotic communities may be vulnerable to elevated sediment.

Baker et al. (n.d.) sought to identify drivers of SS export at TCEF, and to understand the relationship between landscape structure, climate, and suspended sediment export in response to climate variability and forest harvest practices. They found that suspended sediment export from watersheds at TCEF was greatest when watersheds had the combination of complex terrain, wetter weather, and recent forest harvesting.

Hydrologic characteristics of the watershed were strongly related to SS export. The magnitude of snowmelt and SS export were highly positively correlated, while the mean response time (MRT) of the watershed was significantly negatively correlated with SS export. This suggests that the longer the watershed response time, the less sediment is exported from the watershed. MRT for a given watershed was variable from year to year and was a function of SWE, which is an indicator of the volume of water moving through the watershed during snowmelt, highlighting the connection between climatic conditions and SS export.

The study emphasized the significant interwatershed variation in MRT and SS export during wet years with large snowmelt pulses. During wet years, topographic metrics describing the structure of the watershed, such as the mass balance index, distance from outlet, and distance from creek, were the best predictors of SS export. This landscape control on SS export led to highly variable SS export between otherwise similar watersheds (Baker et al., n.d.).

The Baker et al. (n.d.) study also assessed the effect of timber harvest on sediment mobilization in two subwatersheds within TCEF. They found that timber cutting significantly increased both runoff and SS export by an order of magnitude above preharvest baselines. But the magnitude of natural variability in SS export from watersheds was actually greater than the effect of harvesting. Despite the increase in export resulting from timber harvesting, export from some undisturbed watersheds was still greater than that found in the postharvest watersheds. From this study, they were unable to determine what effects harvesting would have in

watersheds with naturally high sediment yields. We hypothesize that a naturally high sediment watershed would respond similarly to other watersheds at TCEF and display increased sediment loads following harvesting.

The Baker et al. (n.d.) study demonstrates the complex interaction among climate, watershed structure, and management disturbance and how the intersection of these various factors leads to the greatest SS export. These findings that areas of the landscape that are highly hydrologically connected to the stream network will influence sediment dynamics disproportionately suggest that harvesting within these zones will have the greatest potential to increase SS export.

Natural disturbance regimes—

Historical pollen and charcoal analyses by Barrett (1993) showed that fires were significant natural disturbances that structured forest ecosystems at TCEF. By mapping and dating historical forest fires at TCEF back to the 1580s, this study provided evidence that for many centuries, fire was a recurring, although episodic, disturbance in this landscape. However, TCEF has been under full fire suppression since the 1940s. No research has been conducted at TCEF on the effects that wildland fire, or its exclusion, has had on terrestrial or aquatic biogeochemistry, or aquatic biological communities.

Insect-induced tree mortality is another natural disturbance that can affect vegetation structure, and that has cascading hydrologic and biogeochemical effects. Kaiser et al. (2013) assessed the impact of the most recent mountain pine beetle (*Dendroctonus ponderosae*) outbreak on tree mortality at TCEF. They found that trees in more water-stressed landscape positions were most likely to exhibit the effects of infestation. Such sites were on south-facing slopes, steep slopes, and sites with small contributing areas that produce low topographic wetness indices. Although the beetle infestation had clear spatial patterns, only about 2 percent of all the trees at TCEF showed signs of infestation in 2012, suggesting that the outbreak was not as severe as in forests in other parts of the Rocky Mountain West and western Canada. Natural disturbances such as fire and insect infestation can strongly influence vegetation structure, which would likely have cascading effects on streamflow generation and solute loading. However, effects of these natural disturbances on streams have not been studied at TCEF.

Reliability and Limitations of Findings

Research at TCEF is based on more than a decade of extensively field-based, spatially distributed empirical data with high temporal resolution. Findings based on these data are highly reliable and are an accurate portrayal of hydrologic response in relatively undisturbed, forested headwater sites with mountainous terrain and

snowmelt-dominated hydrologic regimes. As an experimental forest for the past 50 years, land management at TCEF has been closely controlled.

As with any process- or site-level research, care must be taken in extrapolation to other environments. However, the fundamental hydrologic and biogeochemical understanding generated at this site is likely relevant across a large portion of the Rocky Mountain West. For watersheds where characteristics differ markedly from TCEF's, or where a high degree of accuracy is needed, we suggest validation studies to assess how transferable the findings are and how well they explain patterns at other sites.

Research Needs

High-priority biogeochemical research needs at TCEF that would benefit the water quality regulatory community include explicit investigation of the mobilization and fate of terrestrially derived solutes, including N and P in headwater streams, and what role instream processes have in modifying nutrient dynamics in downstream systems. Filling this need could provide regulatory agencies with improved baseline understanding of natural nutrient retention mechanisms in streams and how this uptake capacity could change across a range of increased nutrient loading in response to anthropogenic disturbances, such as enhanced atmospheric deposition, land development, or agricultural expansion.

This research need might be filled by future research at TCEF, including measurements of nutrient uptake and utilization across a gradient of enrichment concentrations, either through sequences of steady-state enrichments of varying concentrations or through the use of tracer additions for spiraling curve characterization, which characterize the full range of solute kinetics in a single tracer addition (Covino et al. 2010). These experiments would be conducted across seasons, as well as stream network positions, to disentangle the complex relationships between N and P uptake and environmental drivers such as flow state, light availability, and substrate availability.

Studies that began in 2013 (Seybold and McGlynn 2017, 2018) may address parts of this need. Their goal is to more fully link stream ecosystem function and aquatic nutrient processing with their terrestrial hydrological and biogeochemical drivers at this site. These studies are ongoing and will assess the spatial and temporal variability of nutrient availability across the stream network, quantify nitrogen and carbon demand in headwater stream reaches, and help clarify the role of the stream ecosystem in transforming and retaining nutrients from terrestrial watersheds.

Other relevant research needs of regulators that could be addressed at TCEF include more accurate nutrient budgets and improved insight into watershed solute dynamics on diel to weekly temporal scales.

Potential Utility to Water Quality Regulatory Agencies

Findings from existing research at TCEF might greatly aid water quality regulatory agencies by providing insight into the terrestrial hydrologic dynamics that drive solute export from terrestrial to aquatic ecosystems. One important conclusion drawn from research at TCEF is that certain areas of a watershed, for example, riparian areas, are more frequently connected to the stream and thus exert a greater influence on stream solute dynamics than other areas of the watershed such as hillslopes. When considering how a watershed will respond to disturbances, such as forest harvesting, land development, or agricultural use, it is important to consider that the most sensitive parts of the landscape are those that are most consistently hydrologically connected to the stream, because they supply disproportionately more runoff and solutes throughout the year, or during periods of concern, such as snowmelt or low-flow conditions. Improved predictions of differential contributions to streamflow and solute export from different parts of the landscape throughout the year might help regulators identify important areas for protection from disturbance, as well as suspected sources of pollutants of concern mandated by section 303(d) of the Clean Water Act (United States Code 33, sections 1251–1387).

The research at TCEF on the relationship between forest harvest and suspended sediment export are immediately relevant for regulators who are managing and developing timber harvesting regulations to reduce stream sedimentation. The Baker et al. (n.d.) study highlights the difficulty of using single watershed studies to draw universally applicable conclusions about the implications of management decisions. Their findings demonstrate that significant interwatershed natural variability in SS export exists at TCEF. Although they found that sediment flux from most watersheds increased in response to timber harvesting, in some cases, postharvest SS export from a watershed was still less than natural SS export from another adjacent, undisturbed watershed with naturally high levels of SS export. To further complicate this pattern, the magnitude of this effect varied from year to year as a function of climate. Thus, it is difficult to rely on a single watershed, or even paired watershed experiments, to draw conclusions about how all watersheds will respond to harvesting. However, this study does show that easily observable watershed characteristics can likely help explain sediment export variation among watersheds.

The findings of Baker et al. (n.d.) may also inform managers about different locations within a watershed where timber harvesting would make more or less of an impact on stream sediment export. Generally speaking, low slope and low topographic complexity watersheds with large hillslopes have long flow paths that produce low sediment and nutrient fluxes to the stream network. Such information might be useful to regulatory agencies for developing forest harvest rules or guidelines to minimize SS export.

Current and ongoing work at TCEF that seeks to understand the fate of terrestrially derived solutes, including N and P, in stream ecosystems could help inform total maximum daily loads for watersheds in the region, particularly the quantification and allocation of nutrient loading from watersheds where best management practices have been appropriately applied to timber harvesting. The state of Montana has numeric standards for nutrients total P and total N and narrative water quality standards for other pollutants such as sediment. Narrative standards are applied when there is insufficient information to develop numeric standards. The Montana DEQ uses the reference condition approach to assist with many beneficial use determinations for pollutants that have narrative standards. Research data and findings from TCEF could provide a set of reference conditions to assess compliance with narrative water quality standards. Because it has been minimally disturbed, the existing data on stream chemistry could provide a baseline for reference conditions, and data could be augmented by future enhanced sampling campaigns. In particular, sediment is subject to narrative standards, thus the extensive body of research at TCEF on suspended sediment source dynamics and instream concentrations could represent a valuable reference resource. Furthermore, the TCEF nutrient data could be used as a reference condition by other states that have similar watershed characteristics for developing numeric nutrient standards.

Key points:

- Landscape structure is an important and significant driver of hillslope-riparian-stream (HRS) connectivity. HRS connectivity and the mean response time of a watershed are both important parameters for understanding the processes that deliver terrestrial solutes into the stream network, and the degree to which the stream network is buffered from N and P enrichment from the terrestrial landscape.
- Landscape structure also mediates the distribution of environmental drivers (e.g., water, energy, nutrients) that influence the magnitude and patterns of biogeochemical cycling; this is demonstrated by studies at TCEF on the spatio-temporal patterns of land-atmosphere carbon exchange and DOC mobilization.
- Topography, watershed structure, climate, and natural or anthropogenic disturbances are all important drivers of SS export. The greatest SS export occurs when these drivers reinforce each other.
- Each watershed responds differently to the same type of disturbance, partially as a function of the structure of the watershed. The spatial pattern of disturbance on the landscape likely has the potential to magnify or reduce this affect.

- High-priority research that could benefit the regulatory community would focus on quantifying the ability of streams at TCEF to retain and transform terrestrially derived N and P, and assess the impact of instream biotic transformations on downstream nutrient fluxes and water quality.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Water quality issues differ locally and regionally in response to the nature of the watershed and the anthropogenic impacts it is experiencing. In the area surrounding TCEF, hard-rock mining and spoil disposal, especially associated with abandoned mines, can be a source of sediments and, in some cases, high levels of acidity, sulfate, and toxic metals in affected streams. Where they occur, mining-related impacts on water quality can impair beneficial uses such as drinking water, habitat for fish and other aquatic organisms, and water-contact recreation. TCEF has not been affected by either mining or spoil disposal, so measurements there may give indications of background stream conditions in the absence of mining.

Findings From Studies

The USFS monitoring program has collected TCEF stream water concentrations of alkalinity, sulfate, sodium, potassium, chloride, magnesium, bicarbonate, and carbonate at semiannual timescales. These data are available to provide background information for regulators if water quality concerns were to arise regarding one of these solutes. There have not been studies at TCEF on the response of stream communities to any of these specific nutrients.

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

The same hydrological studies that were discussed earlier in reference to N and P would also be applicable to other nutrients. Because the studies primarily describe the hydrologic mechanisms that control solute delivery to streams, these same mechanisms would also probably apply to other nutrients that are derived from the terrestrial landscape.

Reference Watersheds

Semiannual monitoring of stream water concentrations of nutrients other than N and P has been conducted by the USFS since 1992 at Stringer Creek, Upper Tenderfoot Creek, and Bubbling Creek, where these streams drain de facto reference

watersheds (fig. 6.1). As we stated earlier, undisturbed, instrumented watersheds at TCEF with long-term data records are rare and of high value to the regulatory community for establishment of baseline conditions. The USFS monitoring dataset at TCEF is an important resource for managers seeking to establish baseline conditions in undisturbed, reference watersheds.

Dose-Response Studies

No dose-response studies have been conducted at TCEF.

Cross-Site and Regional Studies

TCEF has not been included in any cross-site or regional studies on stream response to nutrients.

Responses to Management and Natural Disturbances

No studies to date have explicitly explored how streams at TCEF may respond to nutrients other than N and P. As a result, the potential impacts of management decisions, land use change, and climate change on the ecological and biogeochemical dynamics of other solutes are not currently known.

Reliability and Limitations of Findings

The wider applicability of future studies at TCEF is discussed in relation to stream N and P. Streams at TCEF are characteristic of undisturbed watersheds in the Rocky Mountain West, thus future findings on how these streams respond to nutrients other than N and P would be applicable at similar sites.

Research Needs

A priority research need of the regulatory community that might be filled by future studies at TCEF would be more detailed understanding of biological and chemical conditions in reference streams draining relatively undisturbed forest basins. Water quality regulatory agencies might use such scientific information as an undisturbed baseline from an intact ecosystem against which to compare streams in humanly disturbed watersheds to assess the degree to which water quality has been degraded by activities such as mining or mine spoil disposal. Future research at TCEF that might address this need would include enhanced stream monitoring of nutrients other than N and P, trace metal dynamics, alkalinity, and pH and comprehensive surveys of stream-indicator taxa that integrate community response to stress from these chemical constituents.

Potential Utility to Water Quality Regulatory Agencies

Existing datasets of stream water nutrients other than N and P in de facto reference watersheds at TCEF might be used by regulatory agencies to establish an undisturbed reference point with which to compare impaired waters to assess the degree of impairment. The value of these data for regulatory agencies would be enhanced if the USFS designated one or more TCEF study watersheds with official status as a permanent reference with minimal onsite human disturbance.

Key points:

- TCEF can serve as an undisturbed reference for future studies to assess the degree of impairment in similar watersheds.
- Future studies and continued monitoring activities at TCEF could help inform regulatory decisions, which may include natural and human-induced disturbances ranging from mining to fire, forest harvesting, grazing, and development at the wildland-urban interface.

Overview and Synthesis

While studies on instream N and P dynamics at Tenderfoot Creek have not yet been published, the hydrologic research conducted there can provide much insight into the hydrologic controls on stream solute dynamics and can provide important insight for water quality regulators trying to understand the response of streams to watershed disturbance or management.

The studies at TCEF demonstrate that watershed outlet dynamics are strongly regulated by both extrinsic factors, such as climate variability, and intrinsic factors, such as the landscape structure and disturbance regime of individual watersheds. At TCEF, the interannual variability of streamflow in a given watershed is strongly driven by climate variation, whereas intra-annual variation between watersheds in hydrologic response is strongly coupled to variation in watershed structure. The topographic structure of a watershed determines the duration over which hillslopes are hydrologically connected to the stream network, as well as which parts of the landscape contribute water and solutes to the stream most frequently. The degree of connectivity also determines how rapidly water stored in riparian zones turns over, thus determining how responsive stream concentrations are and how flashy or transient solute loading to streams may be in response to inputs of rainfall or snowmelt to hillslopes.

The connectivity studies highlighted that certain parts of the landscape exert a stronger influence on runoff generation and solute loading relative to other areas that are less hydrologically active. From a management perspective, not all parts of the landscape are equally sensitive to disturbances; areas of the landscape that have high degrees of connectivity will be more sensitive to disturbance, because anthropogenic or natural disturbances to these areas will result in more dramatic or sizeable alterations in runoff generation and solute fluxes to the stream.

Historically, work at this experimental forest has not focused on water quality and nutrient dynamics directly, although there are studies in progress that seek to address some of these critical data gaps for regulators. The work at TCEF to date has investigated the important role that terrestrial hydrodynamics play in mediating solute loading to stream networks, and has demonstrated that any management disturbance or decisions will have a unique effect on streamflow generation and subsequent nutrient loading to the river network based on the nature of the disturbance, where in the watershed it occurs, and the structure or natural hydrologic regime of the watershed.

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Chapter 7: Ecoregion 6.2.12 Sierra Nevada: Kings River Experimental Watersheds and Teakettle Experimental Forest, California

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Introduction

This chapter synthesizes watershed research that is relevant to water quality regulatory agencies from the Bull site of the Kings River Experimental Watersheds (KREW) and the adjacent Teakettle Experimental Forest (TEF). The chapter summarizes results of studies and environmental monitoring at these sites on ecological processes and forest management practices affecting water quality, and identifies priority research needs of regulatory agencies that might be met by future work.

Site Description

The KREW and TEF sites are in the Sierra National Forest (SNF), California, on the west side of the Sierra Nevada mountain range (lat. 36° 57' 55" N, long. 119° 3' 20" W) (see fig. 7.1). The KREW and TEF span elevations of 2050 to 2490 m. These forests are dominated at lower elevations by mixed-conifer stands of sugar pine (*Pinus lambertiana* Douglas), white fir (*Abies concolor* Lindl. ex Hildebr.), and ponderosa pine (*P. ponderosa* Lawson & C. Lawson) with an understory of mountain whitethorn (*Ceanothus cordulatus* Kellogg). At higher elevations, red fir (*A. magnifica* A. Murray) and lodgepole pine (*P. contorta* Douglas ex Loudon) dominate, with ponderosa pine and white fir also present. Jeffrey pine (*P. jeffreyi* Balf.), black oak (*Quercus kelloggii* Newberry), live oak (*Q. agrifolia* Née), and manzanita (*Arctostaphylos* sp.) occupy shallower soils. Precipitation is highly variable from year to year, ranging from an annual low of 65 cm to a high of 215 cm. Almost no rain occurs in this Mediterranean climate from July through September. Precipitation is 75 to 90 percent as snow, and the average annual air temperature is 8 °C (Hunsaker et al. 2012). The dominant soil is the Cagwin family, a mixed, frigid Dystric Xeropsamment, and the parent material is unglaciated granite (Johnson et al. 2011a). Study streams are perennial, first- and second-order headwaters (table 7.1) with main channel lengths of 2.1 to 3.2 km and slopes of 1 to 12 percent (Hunsaker and Neary 2012). The study area is in the Kings River drainage basin, which terminates in Tulare Lake, an inland lake in the San Joaquin Valley of California.

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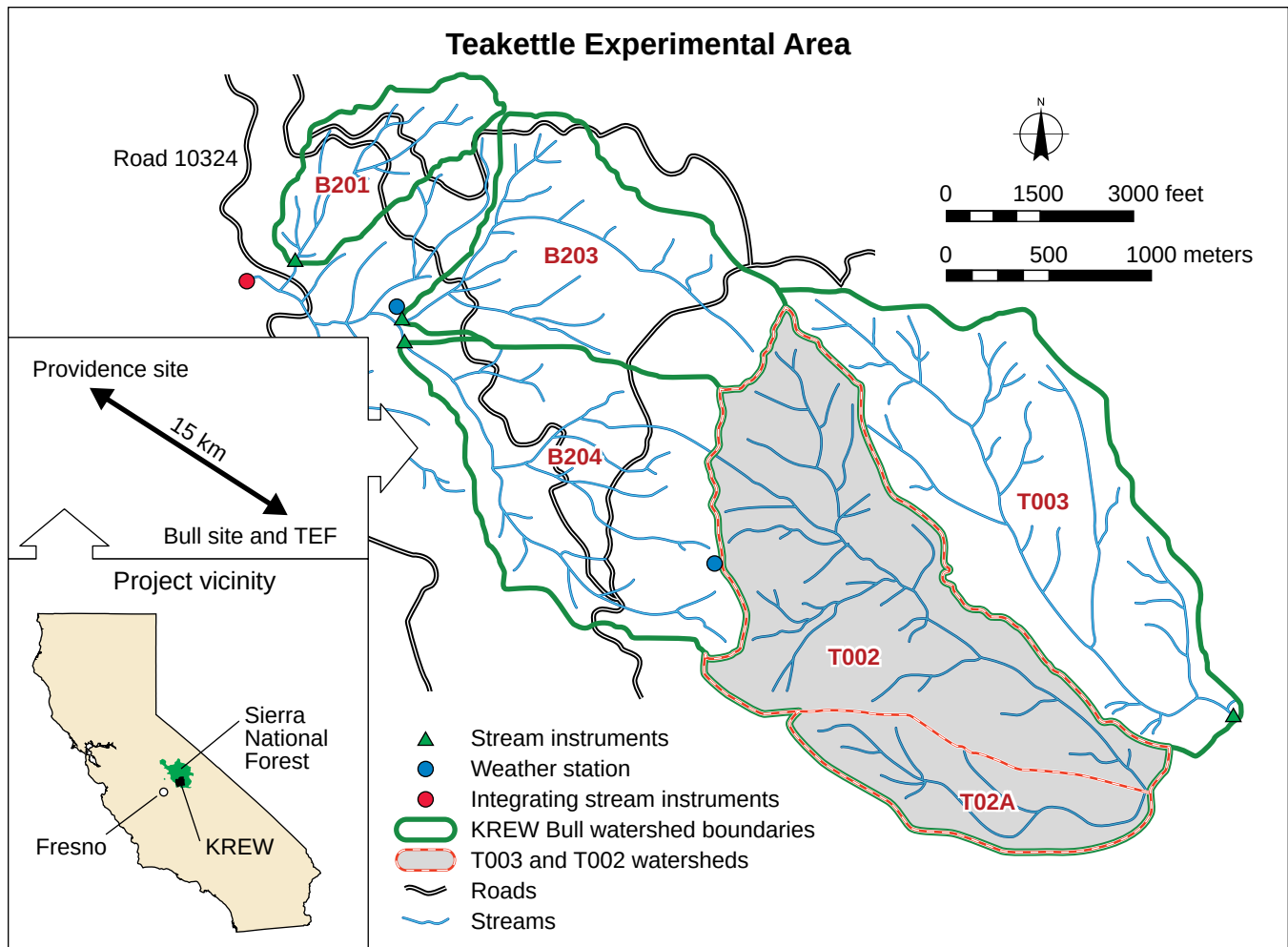


Figure 7.1—Location of the Bull site of the Kings River Experimental Watersheds (KREW) and the adjacent Teakettle Experimental Forest (TEF), including watersheds T003, T002, and T002A, which serve as reference basins with minimal onsite disturbance. Locations of automated instruments for stream measurements and meteorology are shown.

Research History

In 1938, 1300 ha of the SNF surrounding Teakettle Creek were designated as the Teakettle Experimental Area, and several drainages were chosen for study. Stream-gaging stations and sediment basins were built, and geology and soils research began, but studies were halted during World War II. Research resumed in 1957, including regular monitoring of precipitation and stream discharge, and in 1958, the U.S. Forest Service (USFS) officially designated the area as the TEF (North et al. 2002). The initial objective of the TEF was to develop timber harvest techniques that would increase water yield, but shifted to waterflow responses to weather patterns before monitoring was again discontinued in the 1980s. In the 1980s and 1990s, studies of songbirds and snag dynamics began. In 1998, the Teakettle Experiment (North et al. 2002) began studies of alternative methods and combinations of thinning and prescribed burning as strategies to restore the

Table 7.1—Physical and hydrologic characteristics of watersheds T003, B203, and B204

Characteristic	T003	B203	B204
Watershed area (ha)	228	138	167
Mean elevation (m)	2289	2373	2365
Elevation range (m)	2050–2465	2185–2490	2195–2490
Relief (m)	414	303	289
Average slope (%)	24	18	17
Dominant aspect	Southeast	Southwest	Southwest
Drainage density (km/km ²)	5.5	4.6	5.0
Channel length (km)	3.17	2.06	2.16
Dominant soil type (% of area)	Cagwin 94%	Cagwin 80%	Cagwin 98%
Q _{max} (mm/day)	8.46	14.26	11.95
Q _{mean} (mm/day)	1.40	1.80	1.50
Baseflow index (%)	76.1	68.2	68.1
Recession constant (<i>k</i>)	0.027	0.037	0.031
Runoff ratio (%)	33.4	42.9	35.8

Source: Safeeq and Hunsaker 2016.

ecological functions of a natural fire regime using plot-scale treatments that were not located within the gaged TEF watersheds.

In 2000, the USFS Pacific Southwest (PSW) Research Station established the KREW for hydrologic and landscape management research. Objectives of the KREW study included quantifying the variability of important characteristics of Sierra Nevada headwater streams and watersheds (see Hunsaker et al. 2007a) and evaluating effects on streams of forest restoration activities, including tree thinning, commercial timber harvest, and prescribed burning. Restoration goals were to reduce risk of severe wildland fires and to redirect forest structure and composition toward pre-1850 conditions (Hunsaker et al. 2014). The KREW study uses an integrated ecosystem approach that measures an array of physical, chemical, and biological effects of treatments on streams and their watersheds.

KREW instrumentation and treatments were repeated at two sites: the Bull site, which is the focus of this chapter, and the Providence site, approximately 15 km northwest of the Bull site and 400 m lower in elevation. Similar treatments and reference watersheds were implemented at both KREW sites (for details see Hunsaker et al. 2007a). Weekly monitoring of atmospheric wet deposition has been conducted at the Providence site (elevation 1981 m) since 2007 as part of the National Atmospheric Deposition Program (NADP) National Trends Network (NADP 2019).

A portion of the original TEF was included within the Bull site of KREW. In 2003, streamflow monitoring was reinitiated on watershed T003 (formerly named TK3) within TEF, which serves as an undisturbed reference watershed for studies

in the adjacent KREW Bull site (fig. 7.1). TEF watersheds TK2 and TK2A also provide additional reference streams for monitored stream invertebrates as biological indicators for the KREW study.

KREW forest restoration treatments were applied to Bull site watersheds B201 (52 ha), which was thinned in 2012; B203 (138 ha), which was burned in 2013; and B204 (167 ha), which was both thinned in 2012 and burned in 2013. Posttreatment effects are being monitored, but results are not available at this writing. This chapter reports results of pretreatment monitoring and studies of the KREW watersheds and adjacent TEF reference watersheds (KREW/TEF).

Availability of publications and data—

Hydrology and sediment transport data from TEF prior to 2002 were published in Dendy and Champion (1973) and Kattelmann (1989). TEF stream discharge data are available online for 1958–1969 and 1977–1989 (USGS 2017). Daily precipitation and stream discharge data for KREW and TEF watersheds, formatted for ready comparison with other experimental forest and ranges and Long Term Ecological Research sites, are available at the ClimDB/HydroDB website (LTER Network 2017). Long-term meteorological and stream discharge data for KREW from 2002 through 2015 are in the Forest Service Research Data Archive (Hunsaker and Safeeq 2017, 2018). “Geology of the Teakettle Creek Watersheds” (LaMotte 1937) is available online. Some unpublished datasets and historical records from the TEF are available at the PSW Research Station Fresno laboratory (USDA FS, n.d.).

The KREW Research Study Plan (Hunsaker et al. 2007a) contains the study design and maps of the research area. The categories of data collected at KREW are in Hunsaker et al. (2007a). Precipitation chemistry data from KREW (NADP site CA2) are available from the NADP (2019). Publications on KREW/TEF are available online (USDA FS 2017).

Biological Responses to Stream Nutrients N and P

Issues of Concern

Beneficial water uses in the region include domestic water supply, agricultural irrigation, freshwater habitat, water contact recreation, and hydropower generation. Approximately 60 percent of California’s surface water originates in the forested lands of the Sierra Nevada (California DWR 2008). Wildland fire and timber harvesting can cause erosion and resulting sedimentation that reduce water quality and cause loss of water storage capacity of reservoirs (Chapel 2014, Minear and Kondolf 2009). Land management practices, such as forest fuels reduction to decrease the severity of fires and restore forests to presettlement conditions, often entail cutting trees, prescribed burns, or both. Such activities have also raised concerns because they can affect water quality and habitat for sensitive wildlife species.

Usually, forest lands are not a major source of excess nutrient loads (Binkley 2004). However, where long-term nitrogen (N) deposition is high from air pollution, it can cause acidification of forest soil and leaching of N into stream water. In the United States and Europe, this process is generically called “acid rain.” The KREW area has high N loadings from air pollution (Hunsaker et al. 2007b). Lichen species are very sensitive to acidifying effects of N deposition, and acidification of surface water by atmospheric deposition of N can harm fish and invertebrate populations. The southern Sierra Nevada soils and the underlying granite confer significant acid-neutralizing capacity that buffers stream water from acidification. Increases in stream water N may contribute to eutrophication of rivers and reservoirs downstream that can decrease the quality of water for contact recreation, such as boating and swimming, and for drinking water sources. Forest management activities may affect streamflow, nutrient and sediment transport, riparian forest composition, and stream temperature, all of which may alter habitat for fish and other aquatic species.

Findings From Studies

Biological responses to stream nutrients have not been directly studied at KREW/TEF. However, surveys and ongoing monitoring of stream biological communities have been conducted in the pretreatment and reference watersheds where ambient stream nutrients and suspended sediments have also been monitored. We present the monitoring findings and studies of stream biological communities first, followed by stream nutrients and their potential sources and sinks within these watersheds.

Stream biological studies and monitoring—

In the KREW study, biological indicators of stream water quality were selected for monitoring because aquatic communities integrate all environmental conditions and might be more informative indicators of water quality effects from management treatments than physical or chemical parameters. Stream benthic macroinvertebrates were chosen as biological indicators and were sampled repeatedly at the same time of year and location, before and after fuel treatments and on reference watersheds. Samples were always taken in the spring (usually June), and in some years, samples were also collected in fall. Benthic algae are also a biological indicator that was sampled twice during pretreatment (Brown et al. 2008), but they have not been resampled posttreatment.

Benthic macroinvertebrates were evaluated in KREW between 2002 and 2015 for their community structure and densities of total, taxonomic, and functional feeding groups (Herbst et al. 2018, 2019). Ten KREW streams plus two additional TEF streams, T002 and T02A, were monitored for invertebrates (fig. 7.1). Three TEF reference streams were monitored to provide a robust measure of biological

condition of “undisturbed” streams. These data have been analyzed at the finer scale of pools versus riffles and the coarser scale of 100-m-long reaches.

Local flow regimes were an important driver of the structure and abundances of invertebrate communities. Community structure differed between riffles and pools. Total invertebrate densities were higher in pools than in riffles, but the opposite relationship was observed for Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies), groups that are called EPT taxa. EPT taxa are sensitive to habitat degradation and poor water quality. Chironomidae, shredding caddis larvae, and sphaeriid clams were more abundant in pools. These findings indicate that riffles were in better condition than pools throughout the monitoring conducted at KREW.

Benthic algal species assemblages and chlorophyll-*a* standing crop, a measure of stream algal biomass, were measured at KREW in 2002 and 2005 by Brown et al. (2008). Benthic algae were previously little studied in the Sierra Nevada, and the findings of Brown et al. (2008) provided a valuable baseline for using algae as a bioindicator of stream condition in the Sierra Nevada. Periphyton are a complex mixture of algae, cyanobacteria (also called Cyanophyta or blue-green algae), heterotrophic microbes, and detritus that respond to many aspects of the stream environment, including nutrients, that might change with land management practices. Hill et al. (2000) and others have suggested monitoring algal assemblages as indicators of biotic integrity. In addition, benthic algae are also the primary producers in small streams and a food resource for many stream organisms, including macroinvertebrates. Chlorophyll-*a* values in KREW streams ranged from 0.2 to 3.2 mg/m² and were similar to values found elsewhere for small, low-nutrient montane streams and for the larger Merced River, which is north of KREW in the Sierra Nevada (Brown and Short 1999). Benthic algal assemblages in KREW streams were dominated by either diatoms (Bacillariophyta) or cyanobacteria with only a few streams having green, red, or yellow-green algae. Diatoms made up 28 to 94 percent of the algal groups, and cyanobacteria comprised 2 to 68 percent. Diatom species richness ranged from 15 to 47 species and was generally comparable to other studies of western montane habitats, including the Merced River. The most abundant diatom species were *Achnanthes minutissimum*, *Cocconeis placentula*, and *Planorbulina lanceolata*. Diatoms are indicators of good water quality because they are generally sensitive to organic pollution and indicative of high dissolved oxygen levels, low specific conductance, and low dissolved chloride levels. Brown et al. (2008) developed a multivariate model of the effect of stream habitat on diatom abundance in KREW streams; it included elevation, water temperature, pH, specific conductance, and stream canopy cover.

Although steelhead trout (*Oncorhynchus mykiss* Walbaum) may have reached elevations higher than 2200 m in the Middle Fork of the Kings River (Moyle et al. 1996), fish were not selected as biological indicators of stream condition because natural barriers prevented native fish species from being present in the headwater streams of KREW before 1850. Nonnative eastern brook trout (*Salvelinus fontinalis* (Mitchill)) were introduced by humans and have been found in the T003, B203, and B204 streams. These exotic fish were unsuitable as biological indicators because they were not indicative of presettlement conditions (Hunsaker et al. 2014).

Stream water N and P—

Stream water nutrient concentrations from pretreatment monitoring (2004–2011) are compared in table 7.2 for T003 in TEF and two adjacent Bull watersheds, B203 and B204 (fig. 7.1). For the three watersheds, average stream water concentrations in biweekly grab samples for ammonium (NH_4^+) were very similar among watersheds (1.6 to 1.8 $\mu\text{mol}_\text{c}/\text{L}$), but the average concentration for nitrate (NO_3^-) varied almost fivefold from 0.4 $\mu\text{mol}_\text{c}/\text{L}$ in T003 to 2.4 $\mu\text{mol}_\text{c}/\text{L}$ in B204. Average orthophosphate (PO_4^{3-}) concentrations in grab samples were the same for all three watersheds (0.8 $\mu\text{mol}_\text{c}/\text{L}$). Nutrient concentrations in individual, biweekly grab samples were often below detection limits of 0.1 mg/L for NH_4^+ -N and 0.01 mg/L for NO_3^- -N and PO_4^{3-} -P. Grab samples, collected every other week, were biased toward baseflow conditions, and event samples were collected during high flows by automated Teledyne ISCO™ pumping samplers.

Table 7.2—Average stream water chemical concentrations ($\mu\text{mol}_\text{c}/\text{L}$) of biweekly grab samples compared to high-flow event samples taken from T003, B203, and B204 streams with an automated ISCO™ sampler^a

	T003			B203			B204		
	Grab	ISCO	P	Grab	ISCO	P	Grab	ISCO	P
pH	6.93±0.03	7.01±0.04	0.03	6.69±0.03	6.51±0.04	<0.01	6.68±0.03	6.64±0.03	0.18
EC	29±1	24±1	<0.01	15±1	18±1	0.08	19±1	20±1	0.25
Ca ²⁺	174±2	154±5	<0.01	69±1	72±3	0.27	108±3	98±3	0.01
Mg ²⁺	36±0	33±1	<0.01	20±0	22±1	0.11	24±1	23±1	0.11
K ⁺	18±1	32±4	<0.01	11±1	21±3	<0.01	18±3	24±2	<0.01
Na ⁺	82±1	67±2	<0.01	48±1	43±2	<0.01	60±1	50±2	0.08
Cl	11±1	16±2	0.01	10±1	22±4	0.01	12±1	18±3	0.03
NH ₄ ⁺	1.68±0.27	3.00±0.65	0.03	1.85±0.32	3.33±0.42	<0.01	1.63±0.19	2.48±0.26	0.01
NO ₃ ⁻	0.45±0.03	0.57±0.08	0.08	0.93±0.39	5.04±1.46	<0.01	2.44±0.29	7.22±1.36	<0.01
Ortho-P	0.83±0.01	1.43±0.21	<0.01	0.84±0.02	0.87±0.03	0.21	0.84±0.02	0.99±0.08	0.03
SO ₄ ²⁻	7.88±0.51	8.23±0.48	0.32	5.57±0.13	7.05±0.50	<0.01	7.70±0.25	9.41±0.70	0.01

pH = measure of acidity, EC = electrical conductivity (a measure of dissolved solids; used as a generic indicator of pollution), Ca = calcium, Mg = magnesium, K = potassium, Na = sodium, NH₄ = ammonium, NO₃ = nitrate, Ortho-P = ortho-phosphate, SO₄ = sulfate.

^a The probabilities of significant differences between the two sample types are given with significant differences in bold (Student's t-test, P < 0.05).

Comparing results of the two sampling methods showed that NH_4^+ , NO_3^- , and PO_4^{3-} stream water concentrations were all significantly higher during high-flow events (table 7.2), indicating that high flows enhanced nutrient concentrations, rather than diluted them. Ammonium concentrations at high flows were about double the average concentration of grab samples, and the differences were statistically significant at all three sites (table 7.2). Although high-flow concentrations of NO_3^- were higher than biweekly grab samples for all three watersheds, the ratio of biweekly to high-flow NO_3^- concentrations varied considerably among watersheds, ranging from 0.2 for B203 to 0.8 for T003. The ratio of biweekly to high-flow PO_4^{3-} concentrations also varied among watersheds, ranging from 0.6 on T003 to 1.0 on B203.

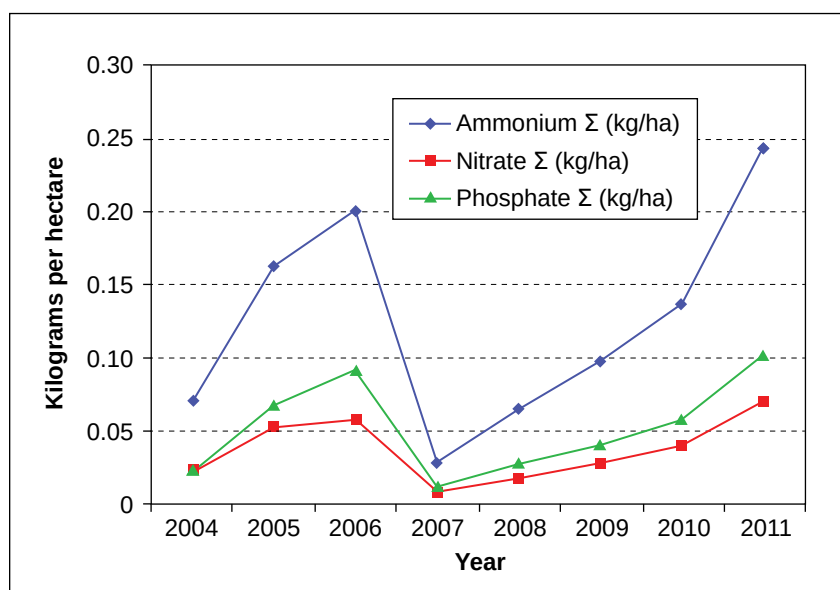


Figure 7.2—Annual flux in stream water of ammonium-nitrogen, nitrate-nitrogen, and phosphate from 2004 to 2011 for reference watershed T003.

Annual stream water fluxes of nutrients from watershed T003 were calculated for water years (WYs) 2004 through 2011 (fig. 7.2). A water year is from October 1 through September 30 of the following year. The fluxes of both N and phosphorus (P) were strongly driven by streamflow, with greatest fluxes in high discharge WYs 2005, 2006, 2010, and 2011; we found that these ions were enriched rather than diluted during high flows. Nitrate-N and PO_4^{3-} -P loads were lower than 0.1 kg/ha/yr in all years. The annual flux of NH_4^+ -N ranged from <0.05 to 0.25 kg/ha/yr and was greater than NO_3^- -N flux in all years.

Sources of N and P from watershed soils and atmospheric deposition—

Watershed soil and atmospheric inputs are sources of nutrients to KREW streams.

Soil physical and chemical characteristics were quantitatively sampled using 87 spatially distributed, 1-m-deep soil pits (Johnson et al. 2011a). The orthophosphate pools in the soil ranged from 75 to 150 kg P/ha, with B204 being the largest.

Nitrate-N and NH_4^+ -N pools in soil were highest in watershed B203 at 23 and 325 kg/ha, respectively, while soil pools in T003 and B204 were similar to each other at 15 kg NO_3^- -N/ha and 200 kg NH_4^+ -N/ha, respectively (fig. 7.3). Rock outcrops lack

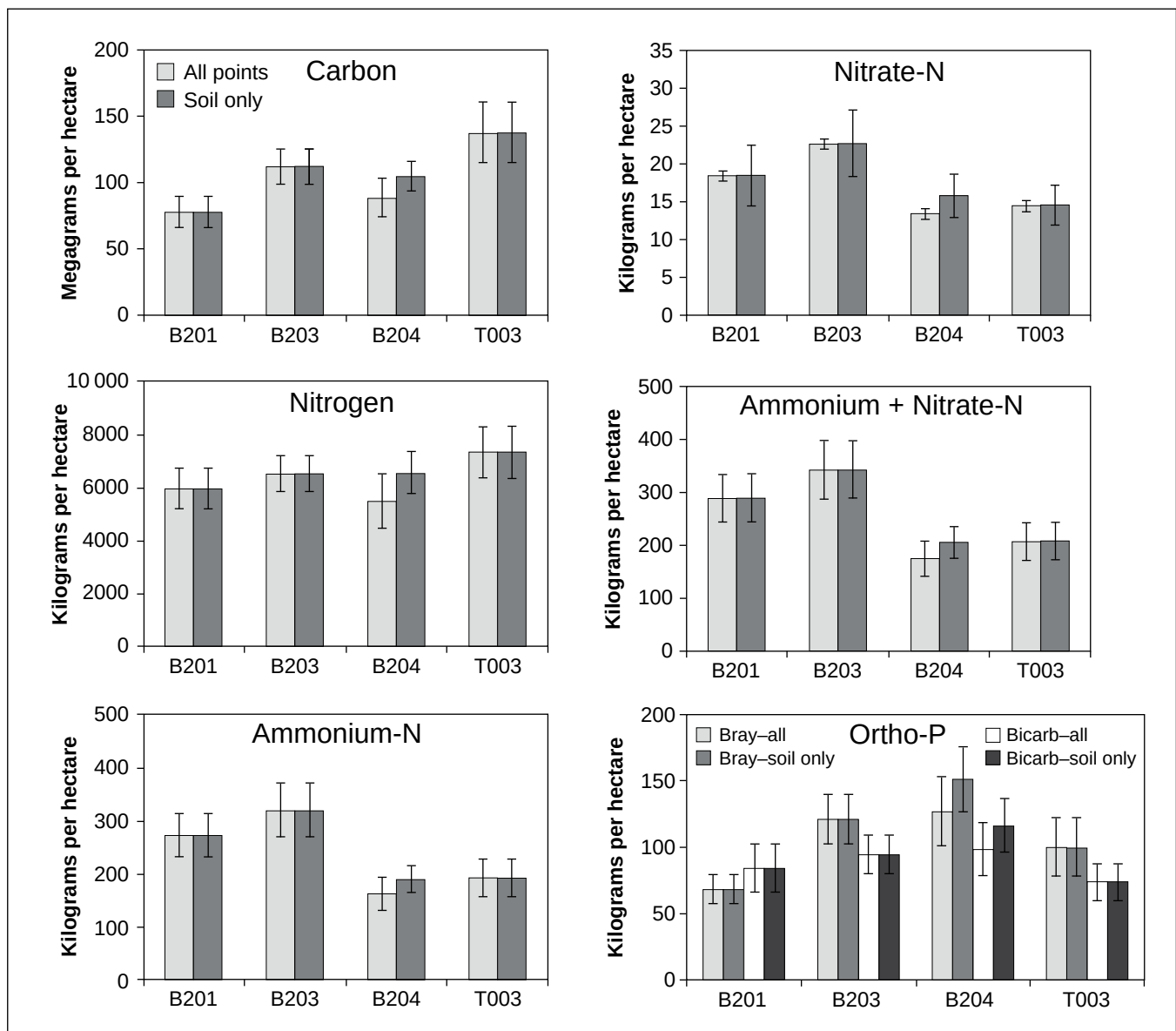


Figure 7.3—Carbon and nutrient pools in the top 1 m of soil for the T003 watershed and the three adjacent Bull watersheds (Johnson et al. 2011a). The data labeled “all” included sample points on bedrock outcrops with no soil. The data labeled “soil only” excluded points on outcrops.

surface soil and are common in these watersheds. Including the effect of outcrops on soil pool sizes, called “all points” in figure 7.3, soil nutrient pool sizes were significantly smaller on B204 than if the effects of outcrops were excluded (called “soil only”), but made no significant difference for T003 and B203. Total N in soil at T003 was highest at ~8000 kg N/ha, while B201 and B204 both had ~6000 kg N/ha. Compared to values reported for other forest locations in the Sierra Nevada, the measured pools of NH_4^+ -N, and mineral N were both high, but the carbon (C):N ratio (22.1 ± 1.6) was similar. Pool sizes of N in watershed soils were consistent with stream water fluxes in that NH_4^+ -N substantially exceeds NO_3^- -N in both. However, soil chemistry alone probably does not explain all aspects of N concentrations in stream water, indicating that other factors, such as hydrology, biological processes, and atmospheric deposition probably also influence stream N levels.

To assess whether deposition of air pollutants is negatively affecting forests, soils, and streams, Fenn et al. (2008, 2011) estimated critical loads of atmospheric deposition for the mixed-conifer forests of the Sierra Nevada. Critical loads are levels of atmospheric deposition below which sensitive components of the forest ecosystem experience no undesirable effects. Sensitive components for Sierra Nevada forests are lichen species that do not tolerate elevated N deposition and streams that could be acidified by increased N deposition. They estimated that critical loads for sensitive lichens were 3 to 5 kg N/ha/yr and for streams were 17 kg N/ha/yr. They further estimated that a background level of atmospheric deposition of N in the southern Sierras, in the absence of anthropogenic air pollution, would be 1 to 2 kg N/ha/yr. Using NADP protocols at KREW, wet atmospheric deposition of total inorganic N, for the WYs 2008 to 2012, measured in an open area that was not under forest canopy, averaged 4.40 ± 1.47 (standard error) kg N/ha/yr. Thus, current levels of N in atmospheric wet deposition alone are considered harmful to sensitive lichen species. The highest annual wet deposition, 10 kg N/ha/yr, measured at KREW in 2008, was below the estimated critical load for damage to streams. However, there is concern that dry deposition of N might cause total N deposition to approach the critical load for streams at times. Dry deposition of N is the net flux from the atmosphere to the watershed in gases, such as nitrogen oxides and ammonia, and particulates, neither of which are efficiently captured by conventional wet precipitation collectors. In forests, dry deposition occurs primarily on the foliar canopy.

A study of internal fluxes of N within the KREW watersheds, using the methods described by Susfalk and Johnson (2002), provided some evidence of the magnitude of the total atmospheric deposition of N and its potential effects on streams. N fluxes in throughfall were measured, as well as the flux of N in soil water leaving the forest floor and entering the underlying mineral soil using ion exchange resin

collectors at points on a uniform 150-m grid across the Bull site (figs. 7.4 and 7.5). Throughfall is precipitation collected under the forest canopy, and it contains the sum of wet plus dry deposition washed from the canopy. Throughfall provides an estimate of total atmospheric deposition, if net leaching of N from foliage is assumed to be negligible. At the majority of sampling points, annual throughfall loads of N were above 2 kg N/ha/yr, which is the background deposition that would be expected in the absence of air pollution (fig. 7.4). At some sampling points, and sometimes for more than 1 year, local extremes of the throughfall N flux were greater than 17 kg N/ha/yr, the critical load of N that would negatively affect stream water, if the average of deposition at all points in the watershed exceeded this value (fig. 7.4). However, the observed annual loads of mineral N in streams were very low (<0.4 kg N/ha/yr) indicating that the limited number of local extreme fluxes of N had only a minor effect on streams. Thus, detailed measurements showed that throughfall N flux is highly variable and that, while locally extreme fluxes can

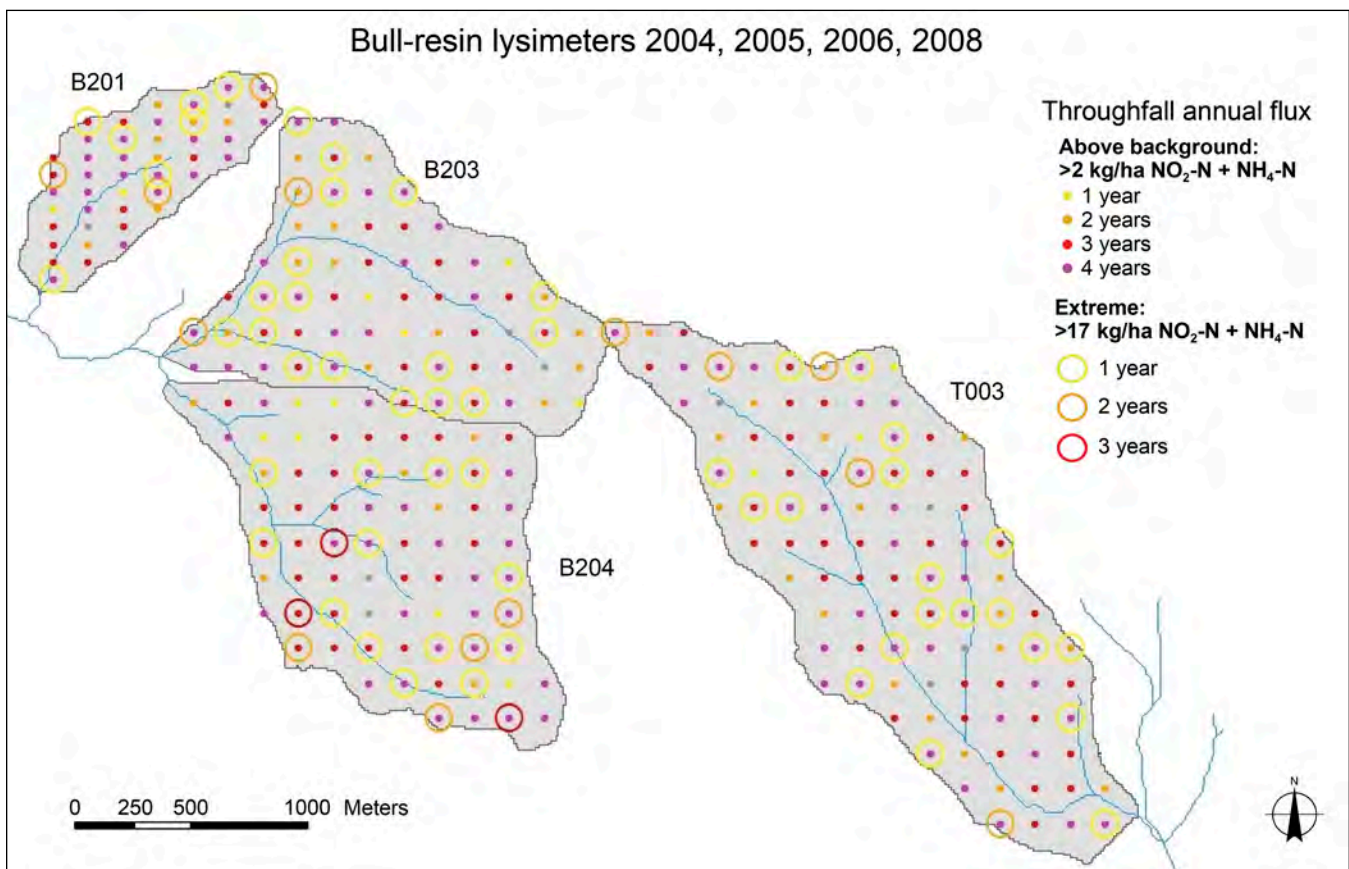


Figure 7.4—The spatial pattern of annual nitrogen flux (nitrate nitrogen plus ammonium nitrogen [$\text{NO}_2\text{-N} + \text{NH}_4^+\text{-N}$]) in throughfall, for 2004, 2005, 2006, and 2008, measured on the Kings River Experimental Watersheds' sampling grid by aboveground ion exchange resin collectors. The estimated atmospheric deposition flux in the absence of anthropogenic air pollution, 2 kg N/ha/yr, was defined as background, and the flux that would negatively affect streams, 17 kg N/ha/yr, was defined as extreme.

exceed the critical load to streams at some points within the watershed, the low N flux measured in stream water indicates that, at the scale of the whole watershed, critical loads of N for streams are probably not being exceeded.

Fluxes of N in soil water provide evidence that N cycling is not spatially uniform within the study watersheds. After entering the forest floor layer as throughfall, soil water is altered by additions of N from sources such as decomposition of organic matter, and N is depleted by sinks such as uptake by soil microbes and tree roots. Resin samplers in the shallow mineral soil (depth 13 cm) found N fluxes elevated above throughfall at the majority of points (fig. 7.5). Locally high (>10 kg N/ha/yr) and extreme (>20 kg N/ha/yr) soil fluxes were found entering shallow mineral soil at some sampling points for 1 or more years. Soil water that drains from the forest floor eventually flows to streams via interflow or groundwater where it may be further altered as a result of N-cycling processes along the way. While N concentrations in stream water have been observed to increase during

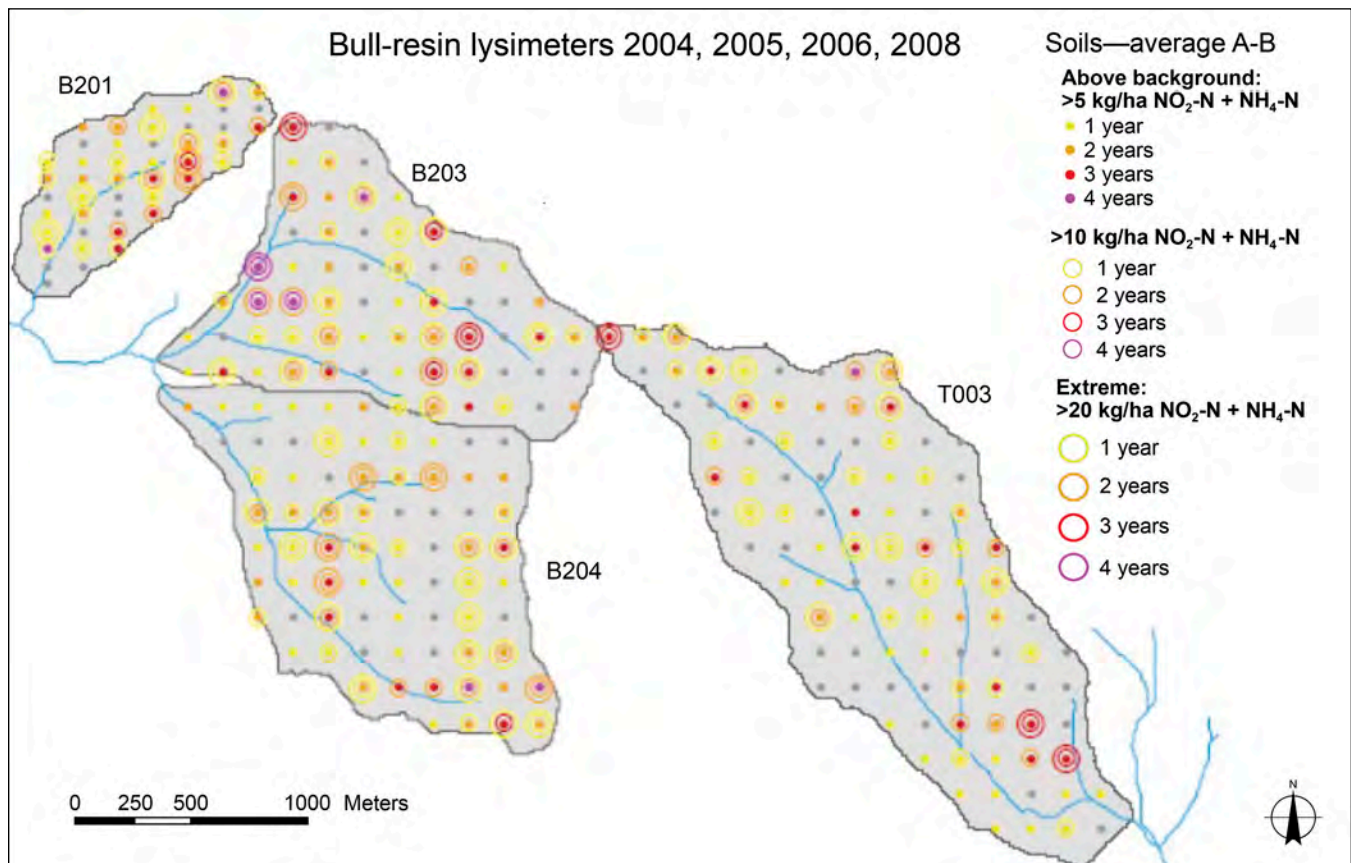


Figure 7.5—The spatial pattern of annual nitrogen flux (nitrate nitrogen plus ammonium nitrogen [$\text{NO}_2\text{-N} + \text{NH}_4\text{-N}$]) into shallow soil, for 2004, 2005, 2006, and 2008, at the Bull site. These values are measured on the King River Experimental Watersheds' sampling grid by ion-exchange resin lysimeters 13 cm depth in the mineral soil. Background (unenriched) level was defined at 5 kg N/ha/yr and extreme level as 20 kg N/ha/yr.

high precipitation events and snowmelt, the increases in stream water N are small compared to the high levels observed in soil water. These locally high values of soil water N may be indicators of “hotspots” of N cycling within the watersheds. The increase in stream N concentrations, at higher flows, suggests that hotspots might be more hydrologically connected to streams during wetter, high-flow conditions. Under dryer conditions, hotspots may be less connected to streams, and vegetation and microbial uptake may effectively retain N produced at hotspots. Consistent with these observations was evidence described by Johnson et al. (2011b) and Woodward et al. (2013) of soil N hotspots in forests at the Providence site. Thus, the flux of N entering the soil surface in throughfall is altered by sources and sinks of N in the forest floor, some of which may produce local hot spots where soil fluxes within small areas exceed levels that would be detrimental to streams, if N loading, on average, was this high over the whole watershed. During wet conditions, increased hydrologic connectivity between hot spots and streams might explain increased N levels observed in streams at high flows. However, the detailed mechanisms of N cycling that ultimately process atmospherically deposited N as it passes through watershed soils and enters stream water are currently not fully understood.

Other Factors Relevant to Biological Responses to N and P

Following an ecosystem approach, scientists at KREW have monitored many environment factors that affect stream N and P and biological responses to them within these watersheds.

Streamflow generation processes—

Processes controlling streamflow generation were analyzed using geochemical tracers and end-member mixing analysis for WYs 2004–2007 on the eight KREW watersheds (Liu et al. 2012). Streamflow in these headwaters was dominated by subsurface flow (about 60 percent of discharge), while snowmelt runoff contributed less than 40 percent and fall storm runoff (overland flow) less than 7 percent. Snowmelt runoff is water that flows overland and has little contact with the soil, while subsurface flow follows the soil-bedrock interface or moves through the soil along preferential pathways and combines water from both rain and snowmelt that has infiltrated into the soil.

Hydrology and watershed characteristics—

Despite the dominance of subsurface flow on an annual basis, precipitation magnitudes and patterns also play important roles in stream hydrology and chemistry fluxes. Hunsaker et al. (2012) and Safeeq and Hunsaker (2016) analyzed KREW meteorology and stream discharge data for WYs 2004 through 2014. Our analysis

of the variability of annual precipitation at KREW/TEF, based on long-term (1981–2010) precipitation data, and using a statistical model (Daly et al. 1994), found that from 2004 to 2014, only 2 years had normal precipitation (125 to 175 cm), while 4 years were above normal (175 to 225 cm), and 5 were below normal (50 to 75 cm).

Although total precipitation during a year determines annual stream discharge, individual stream responses to incoming precipitation are partly governed by the physical attributes of each watershed. For many years, especially during wet WYs 2005 and 2006, B203 had the highest total discharge per unit area, and B204 had the second highest at the Bull site. These rankings also applied to the mean and maximum flows (table 7.1). The ratio of long-term average discharge to long-term average precipitation, called runoff ratio, for B203 was 43 percent, while for T003 it was 33 percent. The runoff ratio is also an indication of the separation of incoming water between discharge and evapotranspiration, assuming no net change in storage and seepage as deep groundwater. Thus, according to this metric, T003 has a greater fraction of incoming water leaving via evapotranspiration than do B203 or B204.

There are several similarities among the adjacent T003, B203, and B204 watersheds, but also substantial differences in hydrologic functioning. Cagwin soils dominate (>90 percent) of all three of these watersheds. The mean elevation of B203 and B204 is about 100 m higher than that of T003. Watershed T003 is larger than B203 and B204 and has a longer channel, a higher drainage density, and a higher average slope. The ratio of base flow to total flow, called the base flow index, was almost 10 percent higher on T003 than for B203 and B204, implying that T003 has a greater groundwater influence and longer flow path than the two Bull watersheds, consistent with its slower base flow recession (Safieq et al. 2013) (table 7.1).

Sediment—

The amount of sediment carried by a stream can be affected by forest management activities. The pool behind the T003 weir and settling ponds below the flumes on the Bull watersheds, have served as sediment collection basins. Hunsaker and Neary (2012) analyzed the KREW watershed bedload data for pretreatment years, assuming that collected sediment was primarily bedload in these granitic watersheds. Because the Bull and Teakettle watersheds receive 75 to 90 percent of their precipitation as snow, soil erosion tended to be lower than for the more rain-dominated KREW Providence watersheds. Variability among streams and years was high because the annual sediment load was related to the annual precipitation, which varied widely, and because large individual flow events contributed substantial fractions of annual loads. Average annual sediment loads from WY 2003 through WY 2009 ranged from a low of 8 ± 11 kg/ha at B204 to a high of 16 ± 21 kg/ha at T003. When we compare the current sediment loads measured at T003 to historical

measurements (Dendy and Champion 1973), we find similar average annual loads with high variability. The 4 years measured between 1940 and 1951 show an annual average load of 18 kg/ha, and the 4 years measured between 1958 and 1962 show a similar annual average load of 20 kg/ha with a range of 1 to 35 kg/ha.

Historical data from TEF and recent data from KREW will allow for an updated sediment budget for the headwaters of the Kings River and will improve assessments of the effects of contemporary forest management practices on sediment and nutrient loads. Reid and Dunne (1996) produced a sediment budget for the North Fork Kings River basin showing that bank erosion was causing half of current total sediment delivery, which they estimated at 16 Mg/km²/yr. Road surface erosion was the only disturbance category they considered, and they estimated that it contributed less than one-quarter of the total sediment yield. Work in KREW and other Sierra watersheds has found similarly that bank erosion is a major component of sediment budgets and that in-channel sources dominate sediment supply (Bales et al. 2015, Kwan and Swanson 2014, Martin 2009, Nolan and Hill 1991).

Stream temperature—

Stream temperature is an important habitat factor for aquatic organisms and has been a concern when riparian vegetation has been removed or trees thinned close to streams. Forests in the southern Sierra Nevada are open and naturally patchy, thus streams receive considerable sunlight. Stream temperature is continuously monitored at the outlet of KREW watersheds. The effects of precipitation and snowpack accumulation on stream temperature were apparent for T003 in WYs 2009 and 2013. In both years, low water temperatures (≤ 2 °C) started in late October, but during 2013, with little snowpack, water temperatures started to increase in mid-February, while in 2009, with a normal snowpack, water temperature increase did not begin until mid-April (Hunsaker and Safeeq 2017, 2018; USDA FS, n.d.).

Dose-Response Studies

Dose-response studies for stream nutrients have not been conducted at TEF or KREW.

Reference Watersheds

The T003 (228 ha), TK2 (220 ha), and TK2A (70 ha) watersheds have been managed for minimal onsite human disturbance since TEF was established in 1938, permitting no management activities such as roads, timber harvest, or mineral exploration (fig. 7.1). No wildland fires larger than 0.1 ha have been recorded since 1910, although there were fires before that time, as was common in the southern Sierra Nevada. The boundaries of the TEF are not fenced. Cattle from adjacent

lands occasionally enter the reference watersheds, but usually exert minimal grazing pressure. The research and monitoring findings from T003, presented in this chapter, are indicative of reference stream conditions, including streamflow, stream nutrient concentrations and fluxes, sediment loads, and stream biological communities, including macroinvertebrates and benthic algae. Only macroinvertebrate data are available for watersheds TK2 and TK2A.

Watershed T003 serves as a reference watershed for the Bull site of KREW and could also represent conditions for undisturbed forested watersheds at this elevation in the southern Sierra Nevada. It is valuable as a site for scientific studies of water quality and the structure and function of forest and stream ecosystems in an undisturbed mixed-conifer forest. The exclusion of confounding onsite human disturbance, for example, makes this a potentially useful site for studying effects of regional and global atmospheric effects on forests and stream water quality. Air pollution, originating from transportation, urban and agricultural sources in central California, does reach this area (Hunsaker et al. 2007b), and analyses of long-term climate records from this region have found signs of long-term warming of air temperature (Cayan et al. 2008).

Cross-Site and Regional Studies

Precipitation chemistry data from KREW (NADP site CA28) have been used in regularly produced regional and national analyses of atmospheric deposition patterns and trends (NADP 2019). The USFS's Sierra Nevada Adaptive Management Study used KREW data in water yield modeling, since the period of record was considerably longer at KREW than for most other headwaters in the region (Bales et al. 2015). Jepsen et al. (2015) calibrated a model with KREW data to investigate how hydrogeology might mediate long-term responses of mountain streamflow to reduced snowfall in a warming climate.

KREW has participated in other regional-scale studies. Goulden et al. (2012) used KREW streamflow data to validate a water balance model that characterized evapotranspiration along an elevation gradient in the Sierra Nevada. The U.S. Geological Survey's Southwest Climate Science Center sponsored a study that used vegetation data from KREW and other forests in the southern Sierra Nevada to evaluate the effect of forest management on forest resistance to drought. The KREW has also participated in the National Science Foundation-sponsored Southern Sierra Critical Zone Observatory (SSCZO 2017) and the National Ecological Observatory Network (NSF and Battelle 2017), both of which collect standardized environmental data from a network of study sites for use in cross-site, regional- and continental-scale geoscience and ecological investigations.

Responses to Management and Natural Disturbances

Korte and MacDonald (2007) and Stafford (2011) measured road and hillslope erosion over three winters during the calibration period of KREW. High variability in sediment production rates was found among years, among different types of road surfaces, and among individual road plots. Native- and mixed-surface roads produced three times the sediment of gravel-surfaced roads. The estimated sediment delivery from roads was compared to the measured sediment yields in three of the lower elevation Providence watersheds. In two of these watersheds, forest roads contributed less than 10 percent of total sediment yield. In the third basin, roads were estimated to contribute 25 to 50 percent of the total sediment yield, and nearly all of the road-related sediment came from a single mixed-surface road that crossed the stream a short distance above the weir pond (Korte and MacDonald 2007).

These results were consistent with earlier work in the central Sierra Nevada (Coe 2006, MacDonald et al. 2004), indicating that native-surface roads are usually the primary anthropogenic source of sediment in this region. Coe (2006) and Stafford (2011) suggested that sediment delivery from forest roads could be reduced by (1) reducing the length of roads draining to stream crossings and covering them with crushed rock, (2) minimizing the number of stream crossings, (3) minimizing road grading, and (4) improving placement and design of road drainage structures. These guidelines have been used in road-related training courses for California state agency personnel and registered professional foresters.

In the past, natural disturbances for landscapes such as KREW/TEF consisted primarily of wildland fires and extreme climate events. Wildland fires have been effectively excluded by fire suppression activities since the 1930s. The prolonged drought from WYs 2012 through 2015, with drastically low snow amounts, provided recent opportunities to observe hydrologic and ecologic responses to this climate extreme, but analyses have not yet been published.

Reliability and Limitations of Findings

Research results and monitoring datasets from KREW/TEF are most applicable to central and southern Sierra Nevada forests. They also might be relevant for other mountain forest areas with similar climate, steep topography, and granitic soils, such as the Rocky Mountains. TEF findings are useful because they are from watersheds with little human disturbance. The other KREW watersheds have experienced commonly used forest management practices such as timber harvests, tree plantations, hazard tree removal, and road networks. Clearcut harvesting was not extensively used here, although clearing of a few acres of trees sometimes took

place after insect outbreaks produced tree mortality. If environmental factors such as soils or land use are substantially dissimilar, or a high degree of accuracy is needed, we suggest considering validation monitoring or experiments to test how well results from KREW/TEF predict local conditions elsewhere.

Research Needs

The highest priority research need of the regulatory community related to N and P that might be filled at KREW/TEF is monitoring of long-term effects of forest fuels treatments on water quality, including biological indicators, and stream loading and export of N, P, and suspended sediments. These science needs include effects on stream water quality over the first two to three decades following fuels treatments, and ultimately understanding the long-term effects on the stream and watershed ecosystem of regularly repeating these treatments every 25 to 30 years. Such data could then be compared to nutrient and sediment export documented from high-severity wildfires in the Sierra Nevada (e.g., Murphy et al. 2006, Oliver et al. 2011), providing a much needed comparison between prescribed fire and wildfire effects. Regulatory agencies could use these data to assess the effectiveness of current practices and to develop science-based standards and best management practices for future fuels treatments that are sustainable and protect water quality in the Sierra Nevada.

The KREW fuel reduction treatments provide opportunities to study post-treatment effects on water quality that can be compared to both pretreatment data and conditions on the nearby undisturbed reference watershed. Limited data on short-term treatment effects are available for the Lake Tahoe Basin (Stephens et al. 2004) and Sequoia National Forest (Engle et al. 2008). Water quality monitoring at KREW/TEF, including nutrients, sediments, and macroinvertebrate biological indicators, is currently supported by PSW Research Station, and some past support was provided by the California Bay Delta Program, but continuation depends on the year-to-year availability of funding and personnel. Assuring long-term monitoring of water quality effects of the KREW treatments will require resources dedicated for that purpose. Posttreatment monitoring of benthic algae as a biological indicator is not currently supported and would require additional resources. Long-term effects on water quality of regularly repeating fuels treatments in the future might be assessed by developing a model that could be improved with results from the KREW experiment. However, such modeling is not planned as part of the KREW experiment and would require additional resources.

Some other interesting research questions that might be answered at KREW/TEF, but that are of lower priority for the regulatory community, include the following:

- How do the effects of riparian restoration using mechanical thinning and prescribed fire in riparian areas vary within different vegetation types and stream sizes (Van de Water and North 2011)?
- Would updating the KREW sediment budget produced by Reid and Dunne (1996), using geochemical tracers that identify sources of sediment (Belmont 2013), improve assessments of the effects of contemporary management practices on sediment and nutrient loads?
- How do prescribed fire and wildland fire affect the quality of public drinking water sources, especially dissolved organic matter (DOM) and DOM precursors of halogenated disinfection byproducts (Kuhn et al. 2014, Wang et al. 2015)?
- How does atmospheric deposition of N from air pollution affect stream water quality, and how might deposition be affected by climate change?
- What threshold levels of N and P enrichment will produce undesirable biological responses in Sierra Nevada headwater streams?

Potential Utility to Water Quality Regulatory Agencies

The results from the studies conducted to date in the KREW/TEF research watersheds have been used several ways by California's regulatory agencies. For example, these agencies have used the KREW research findings documenting the effects of forest roads on water quality (Stafford 2011) for road design and maintenance training for agency personnel and registered professional foresters, and for developing improved forest practice regulations related to roads.

Stream biotic communities, including algae and macroinvertebrates, have been surveyed in KREW/TEF reference stream, where detailed ambient stream nutrient chemistry has also been systematically monitored. Such data might be useful to regulatory agencies as scientific evidence of undisturbed reference stream conditions for use in developing water quality criteria or standards for Sierra Nevada headwater streams.

KREW/TEF monitoring results can be used to help evaluate the potential effects from proposed land management activities, including timber harvesting, in the central and southern Sierra Nevada. Sediment and turbidity data from the KREW watersheds with fuel reduction treatments and reference streams might be compared to data being collected from intensively managed industrial timberlands in the Sierra Nevada to assess the effects of contemporary timber harvest operations on water quality. For a regional comparison, KREW fuel treatment effects on water quality might be compared to those reported by Bales et al. (2015) for central

and southern Sierra Nevada watersheds. These findings and others from KREW have been used by agencies, including the State Water Resources Control Board, California Department of Forestry and Fire Protection, California Board of Forestry and Fire Protection, California Department of Water Resources, Sierra Nevada Conservancy, and the Bay Delta Program.

The TEF watersheds have some of the longest flow records for small headwater Sierra Nevada streams. Streamflow data from Teakettle Creek watersheds (McGurk 2001, USGS 2017) have been used for flood flow frequency analyses used to validate flow estimation methods for proper design of watercourse crossings (Cafferata et al. 2017). Streamflow data from these watersheds also have potential to be valuable for predicting the effects of large rain-on-snow events in the Sierra Nevada.

Findings from KREW/TEF are potentially useful for predicting how forest management will affect water yield and other aspects of stream ecosystems. The Southern Sierra Integrated Regional Water Management Plan (2014) for the Sierra Nevada south of the San Joaquin River discussed the importance of KREW to the region and noted that it was the only long-term research study in the planning area. An approved plan is required for state funding of water projects including new infrastructure, as well as fuel reduction work and forest restoration. Results from KREW have also been used to inform project planning by local and regional groups such as the Sustainable Forests and Communities Collaborative and the Dinkey Collaborative Forest Landscape Restoration.

Key points:

- Although stream water N is currently low in southern Sierra Nevada headwater streams, increased N might cause undesirable eutrophication and stream acidification. Sources of stream N include atmospheric deposition and forest disturbance by forest management or wildland fire.
- Long-term monitoring has measured baseline levels of N and P and biological communities in streams draining KREW watersheds before and after they were treated with typical fuel-reduction practices and in a reference stream that will remain untreated.
- Ecosystem inputs of N and P in atmospheric deposition have been monitored at KREW, and ecosystem pools of these nutrients have been quantified in soils.
- During high flows, N concentrations in the streams increase rather than become diluted.
- Discharge variability is high both within and between years for headwater streams in this Mediterranean climate, and hydrologic processes can differ even for small, adjacent watersheds within similar landscapes.

- The highest priority science need of water quality regulatory agencies that might be filled at KREW would be a better understanding of long-term ecosystem effects of forest management treatments to reduce wildland fire hazards, especially regarding impacts on water quality, stream biological communities, and riparian zone functions.
- Regulatory agencies might use existing long-term, high-quality data on the physical, chemical, and biological components of the undisturbed reference watershed to develop ecosystem models to better understand processes and predict stream responses to changing environmental conditions, such as warming climate and increased deposition of air pollution.
- Effects of forest management on watershed processes, such as sediment yield from roads measured at KREW, have been used in the design and refinement of forest management regulations. Studies of effects of typical forest practices on streams are currently underway at KREW and are also expected to be useful for regulatory purposes.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Nutrients other than N and P are not generally a source of area-wide concern in forested areas of the Sierra Nevada. However, in some local basins, drainage from active or abandoned mines or spoil disposal sites may degrade water quality by introducing high levels of sediment, acidity, sulfate (SO_4^{2-}), iron (Fe), manganese (Mn), and other toxic metals to surface water. KREW and TEF do not have a history of substantial mining, and so may serve as a baseline for stream conditions in the absence of mining disturbance.

Although carbon (C) is not a nutrient for the purposes of this report, C interacts strongly with nutrients, and storage and emissions of C in forests are a growing concern in California and globally because they affect climate warming. Sierra Nevada forests are regionally important for C storage and their effects on the carbon budget. Processes that play roles in forest C storage include wildland fire, prescribed fire, tree thinning, commercial timber harvest, and tree mortality caused by insect outbreaks. Storage of C is likely to be an important factor in future regulation of California forest management practices.

Findings From Studies

The KREW/TEF research has measured potassium (K^+), SO_4^{2-} , magnesium (Mg^{2+}), and calcium (Ca^{2+}) in stream water and soil. There are stream-to-stream variations

among these nutrients. Concentrations of several of these nutrients were often higher in the undisturbed reference watershed, T003, than for the companion KREW streams during the pretreatment period (table 7.2). For all watersheds, the average stream water concentrations of K^+ and SO_4^{2-} increased during high flows, similar to the flow response of stream N and P, whereas Ca^{2+} and Mg^{2+} did not. These responses to flow were consistent with findings of Godsey et al. (2009), who reported nearly chemostatic behavior for rock weathering products such as Ca, Mg, and increased concentrations with flow for more biologically active ions such as K^+ and NO_3^- in a study of 59 geochemically diverse and undisturbed U.S. watersheds. Thus solute concentrations in KREW streams are not explained by a conceptual model in which a fixed flux of solutes is diluted by a variable flux of water.

Consistent with patterns observed in stream water concentrations, Ca^{2+} pools in soils were significantly higher, and SO_4^{2-} -S pools were significantly lower on watershed T003 than in soils of adjacent watersheds B203 and B204 (Johnson et al. 2011a). Mechanisms that cause the differences among soil nutrient pools in these adjacent watersheds are not well understood.

Monitoring of wet deposition at the KREW NADP site (CA28) has included K^+ , SO_4^{2-} , Mg^{2+} , and Ca^{2+} . Rates of deposition of these elements are similar to other monitoring sites in the southern Sierra (Yosemite as well as Sequoia and Kings Canyon National Parks), but higher than values measured in the northern Sierra that are less affected by air pollution.

Other Factors Relevant to Stream Nutrients Other Than N and P

As was mentioned earlier in this chapter, numerous environmental factors that may influence biological responses to nutrients other than N and P have been measured at KREW/TEF, including streamflow, sediment transport, and temperature. In addition, soil carbon storage at KREW/TEF was found to vary among these watersheds. Soil carbon storage in T003 was significantly higher at 140 Mg C/ha, than in watersheds B203 and B204, which both had C storage of 120 Mg C/ha (Johnson et al. 2011a). A possible explanation for this difference in soil C storage may be that B203 and B204 were disturbed by previous onsite management activities, while T003 was not.

Dose-Response Studies

Dose-response studies of stream nutrients have not been conducted at KREW/TEF.

Reference Watersheds

Monitoring of the stream draining reference watershed T003 has measured stream water concentrations of Ca^{2+} , K^+ , Mg^{2+} , and SO_4^{2-} and their responses to streamflow. Other work quantified the soil pools of Ca^{+2} , SO_4^{2-} , and C in this undisturbed watershed (Johnson et al. 2011a).

Responses to Management and Natural Disturbances

Fuel reduction treatments, including prescribed fire and mechanical thinning, have been estimated to increase forest carbon storage in the long term by shifting growing space from many small trees to fewer large, old trees while reducing loss of stored C from high-intensity wildland fires (Gonzalez et al. 2015). However, effects of these practices on C storage have not been thoroughly tested. Based on a carbon balance for the first 10 years after thinning and burning of plot treatments at TEF, Wiechmann et al. (2015) estimated that understory thinning and prescribed burning can help stabilize forest carbon and restore ecosystem resilience. Stacy et al. (2015) measured pretreatment erosion-induced stream export of soil carbon in the eight KREW streams. Because these forests had low soil erosion rates, they concluded that erosion in these forest ecosystems is not likely to be a significant C sink. Measured C concentrations in sediment from WYs 2009 through 2011 ranged from 16 to 120 g/kg, with T003 having the highest concentrations. Although 30 to 50 percent of the annual sediment load consists of organic matter (Hunsaker and Neary 2012), it is not known over the long term how much of this organic matter is stabilized and thus contributes to the erosion-induced C sink in benthic sediments. Stacy et al. (2015) concluded that croplands and grasslands are larger contributors to the erosion-induced C sink than forests such as those at KREW/TEF. Effects of natural disturbances, such as severe wildland fire and insect-induced tree mortality, on C storage and nutrients other than N and P have not been studied at KREW/TEF.

Reliability and Limitations of Findings

Research results and monitoring datasets from KREW/TEF that are related to nutrients other than N and P, are probably applicable to other central and southern Sierra Nevada forest areas. They also could be relevant for other forest mountain areas with similar climate, steep topography, and granitic soils, for example, in the Rocky Mountains. If environmental factors such as soils or land use are dissimilar to KREW/TEF, or a high degree of accuracy is needed, we suggest considering validation monitoring or experiments to test how well results from KREW/TEF predict local conditions.

Research Needs

The highest priority research need of the regulatory community that is not directly related to N and P that could be filled at KREW/TEF is an improved scientific understanding of the effects of fuels management treatments and forest restoration on carbon cycling and export, especially for soil carbon for forests in the southern Sierra Nevada. Filling this science gap would be important for regulatory agencies because research results from KREW/TEF might be used

to produce more accurate estimates of the effects of fuels reduction treatments on carbon budgets for Sierra Nevada forests. Such information could be used to develop regulatory strategies to sequester carbon and reduce greenhouse gas emissions in California (Battles et al. 2014). Future work at KREW/TEF that might help fill this need includes (1) investigations of changes in C storage in soils and standing and downed biomass as a result of fuels reduction treatments; (2) studies of effects of treatments, compared to reference watersheds, on export by erosion and stream transport of dissolved and particulate C that follows up on work by Stacy et al. (2015); and (3) measurements of emissions from streams and soils of greenhouse gasses such as carbon dioxide, methane, and nitrogen oxide. Although the recent KREW fuels treatments might offer opportunities to fill these needs, such studies are not currently planned. Implementing them would require additional resources.

Potential Utility to Water Quality Regulatory Agencies

A number of existing research results and monitoring datasets from KREW/TEF related to nutrients other than N and P may be of immediate practical use to water quality regulatory agencies. Stream water chemistry and biological indicator monitoring data from reference watershed T003 might serve as a baseline undisturbed headwater stream for assessing impacts of mine drainage in basins disturbed by mining in the southern Sierra Nevada. Trends in atmospheric deposition and stream water concentrations and fluxes of nutrients, such as SO_4^{2-} that have been measured at KREW/TEF, might be used by regulatory agencies as early indicators of how regional levels of air pollution may affect water quality in the southern Sierra Nevada. Results from previous studies of C storage in soils at KREW/TEF might be useful to regulatory agencies for developing or improving models of C storage and fluxes in Sierra forests and how they might be affected by fuel treatments. Quantitative measurements of C storage in the undisturbed T003 basin (Johnson et al. 2011a) and stream flux (Stacy et al. 2015), along with published studies on effects of forest fuels treatments on C storage (Wiechmann et al. 2015), might be useful for developing such models.

Key points:

- Nutrients other than N and P are not currently associated with water quality issues in most of this region, but sequestration and emission of C from forests are a significant concern because of their effects on climate warming.
- Several nutrients other than N and P have been monitored at KREW in stream water and atmospheric deposition, and pools of them have been measured quantitatively in watershed soils.

- Understory thinning and prescribed burning may increase C sequestration in Sierra Nevada forests under some silvicultural approaches, but additional data collected over longer time periods are needed to increase confidence in this outcome.
- The highest priority regulatory research need that might be filled at KREW/TEF that is unrelated to N and P would be a better scientific understanding of the short- and long-term effects of forest fuels treatments on forest C storage and exports. Although KREW management treatments offer opportunities to fill this need, such studies are not planned and would require additional resources.

Overview and Synthesis

The research at KREW/TEF has great potential as a source of useful science for water quality regulatory agencies. Because the Sierra Nevada provides about 60 percent of California's water for agriculture and urban uses (California DWR 2008), findings are useful for both human and ecosystem needs. This project is studying important questions about how land management treatments that are being used in this region are affecting water quality and quantity. Specifically being looked at is whether these treatments reduce the risk of severe wildland fires and restore ecological integrity and resilience. Because the confounding influences of land use have been controlled at this site, it also presents opportunities to monitor and study the effects of warming climate and regional air pollution on water quality in these mountain streams and forests. The value of this study is enhanced because much of it has been initiated since 2003, using scientific and technical approaches that are up-to-date and of high quality. KREW, for example, is the only watershed study in the southern Sierra Nevada that has taken an integrated ecosystem approach that investigates a broad suite of biological, physical, and chemical environmental processes. This whole-system perspective makes it possible to study underlying mechanisms and cause-and-effect relationships that provide scientific bases for modeling stream responses to land management. In addition, environmental measurements at KREW/TEF have used state-of-the-art instrumentation and analytical methods, which produce environmental data with high-frequency and resolution. Examples include quantitative measurements of soil carbon pools, spatially distributed throughfall and soil solution nutrient concentrations, and high-frequency monitoring of stream water nutrients during runoff events. The watershed-scale management experiments underway at KREW/TEF provide opportunities to help answer important, practical questions, such as how fuels management treatments in the Sierras may affect water quality, and C emissions and, at the same time, more basic ecological questions, such as how Sierra Nevada stream ecosystems respond to changing environmental conditions such as drought and wildland fire.

Key points:

- The KREW/TEF watersheds are the only study area that takes an integrated ecosystem approach in the southern Sierra Nevada, which is an important source of water supply for the state of California.
- Studies address important practical questions about how water quality is affected by land management practices used in the region to reduce the severity of wildland fires and to restore forest structure and composition toward conditions that are resilient to natural disturbances and to potential anthropogenic stresses, such as climate change and air pollution.
- Scientific and technical approaches at KREW/TEF are up-to-date and have strong potential to produce useful results for water quality regulatory agencies.

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Chapter 8: Ecoregion 6.2.12 Sierra Nevada: Sagehen Experimental Forest, California

Kristen Wilson and Dale W. Johnson¹

Introduction

This chapter synthesizes environmental monitoring and studies performed at Sagehen Experimental Forest (SHEF) that are relevant to water quality regulatory agencies and suggests research needs of importance to regulators that might be met at SHEF.

Site Description

SHEF lies on the eastern side of the northern Sierra Nevada Mountains in California (lat. 39° 25' 54" N, long. 122° 14' 19" W). SHEF occupies a watershed of 27 km² with an elevation range of 1900 to 2600 m (fig. 8.1). Sagehen Creek drains SHEF to the Truckee River via the Little Truckee River. SHEF is within the Truckee Ranger District, Tahoe National Forest. A small portion of the watershed, about 1 km², is owned by The Nature Conservancy and is managed in a natural condition. The University of California, Berkeley, received a U.S. Forest Service (USFS) special-use permit in 1951 to conduct research in the basin of Sagehen Creek, and since then has continuously operated Sagehen Creek Field Station. SHEF was formally established in 2005, when the USFS Pacific Southwest Research Station assumed administration of the site.

SHEF is predominately mixed-conifer forest, with about 10 percent of the land in meadows. Lodgepole pine (*Pinus contorta* var. *murrayana* Douglas ex Loudon ssp. *murrayana* (Balf.) Critchfield) occurs along Sagehen Creek and moist meadows; Jeffrey pine (*P. jeffreyi* Balf.), ponderosa pine (*P. ponderosa* Lawson & C. Lawson), and sugar pine (*P. lambertiana* Douglas) occur on south-facing slopes. Jeffrey pine, sugar pine, white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), red fir (*A. magnifica* A. Murray bis), incense cedar (*Calocedrus decurrens* (Torr.) Florin), mountain hemlock (*Tsuga mertensiana* (Bong.) Carrière), and mountain mahogany (*Cercocarpus betuloides* Nutt.) occupy the north-facing slopes (USDA FS 2014). There is a plantation of ponderosa and Jeffrey pine planted following wildland fires in the 1960s and 1970s. Quaking aspen (*Populus tremuloides* Michx.) is found in patches, and shrub vegetation, including snowbrush (*Ceanothus velutinus* Douglas ex Hook.), green-leaf manzanita (*Arctostaphylos patula* Greene),

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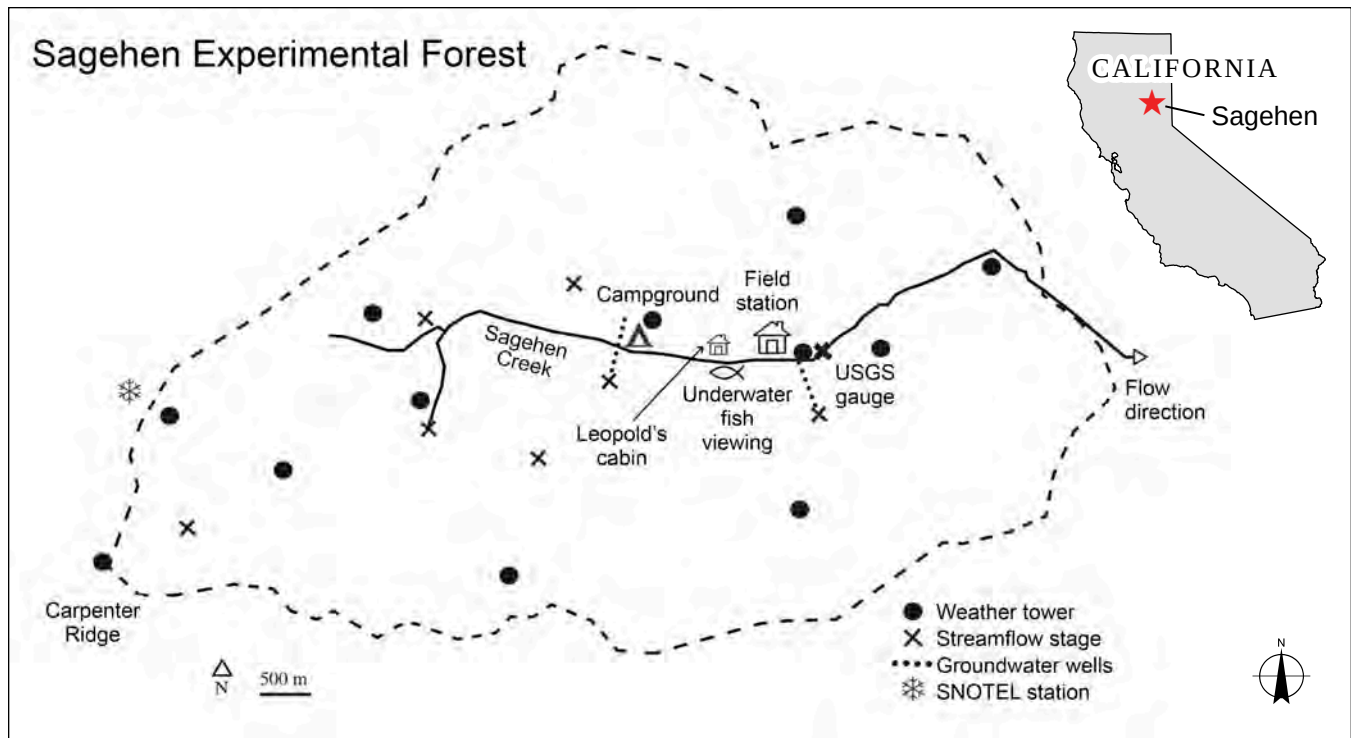


Figure 8.1—Sagehen Experimental Forest with the location of the creek, monitoring stations, and buildings.
USGS = U.S. Geological Survey. Snotel = snow telemetry.

prostrate ceanthus (*C. prostratus cenothus* Benth.), wax currant (*Ribes cereum* Douglas), goldenweed (*Ericameria bloomeri* (A. Gray) J.F. Macbr.), dwarf serviceberry (*Amelanchier pumila* (Torr. & A. Gray) Nutt. ex M. Roem.), and woolly mule ear (*Wyethia mollis*), occurs on poor soils and as a successional stage following wildland fire and logging.

SHEF is steep at its headwaters and flattens into meadows in an upland basin. Soil parent materials are alluvium and glacial till derived mainly from andesitic bedrock (Sylvester 2015). Soils in upland forests are mainly acidic Andic and Ultra Haploxeralfs that have a 50-cm-deep A horizon and are well-drained gravelly or sandy loams or cobbly loam. In wet meadows and fens, the soils are poorly drained Aquolls and Borolls (USDA FS 2014).

SHEF has a Mediterranean climate with cold, wet winters and warm, dry summers. At the field station, elevation is 1936 m, annual precipitation averages 85 cm, and annual snowfall is 515 cm, with both being highly variable year to year. The average daily temperature in the winter is -3 °C, and in summer, 14 °C. Streamflow is largely driven by snowmelt, with mean monthly discharge of Sagehen Creek at the field station gage ranging from 2.2 m³/s during melt off in late winter or spring to 0.04 m³/s during the late summer and fall. There are 14 perennial groundwater springs within SHEF. From its headwaters to the reservoir downstream, Sagehen Creek was recommended by the USFS for scenic designation under the National

Wild and Scenic River Act (USDA FS 1999). The Tahoe National Forest Land and Resource Management Plan recommends that Sagehen Creek be managed to preserve scenic values while Congress considers its preservation status.

SHEF has few roads and has received a relatively low level of management disturbance in recent decades. Since the 1980s, low-intensity logging operations for fuel breaks, salvage, or select/seed tree harvest have occurred on ~28 percent of SHEF watershed (USDA FS 2013). Public access to SHEF for recreation occurs on USFS roads within the basin. The Sagehen Creek Field Station permit area is gated, and vehicle entry is controlled by the station manager.

Historically, SHEF was logged from the 1870s to the 1930s, when a saw mill and logging railroad were built in the watershed. Most merchantable pine within the basin was removed for timber before 1936, when the USFS purchased the land. A grazing allotment that was discontinued in the 1980s permitted 1,400 sheep on the large meadows within SHEF. Prior to widespread fire suppression, this area of the Sierra Nevada experienced periodic wildland fires. The Donner Ridge Fire, which burned one-third of SHEF in 1960, was the last major fire. Suppression has locally prevented major fires since then, but, in recent decades, accumulating forest fuels in the basin have increased the potential for large, high-intensity wildland fires.

Research History

Research at SHEF produced 349 research articles published from 1953 to 2014 as well as 15 studies on adjacent areas of the eastern Sierra Nevada. Since 1953, U.S. Geological Survey (USGS) has gaged stream discharge on Sagehen Creek at the field station (fig. 8.1), a site later designated a USGS benchmark monitoring station. Weather data have been collected at the site since 1953 and more recently expanded to an elevational transect of six weather stations (University of California, Berkeley 2003a, 2003b). In the early decades, research at SHEF focused on fisheries: hatchery management, winter survivorship, and spawning of rainbow trout (*Oncorhynchus mykiss* Walbaum) (Butler and Hawthorne 1968, Needham 1953, Needham and Garb 1959, Needham and Jones 1959, Newman 1956, Sheldon 1968). During that time, there was also research on benthic macroinvertebrates (Sheldon 1969, Sheldon and Jewett 1967), wasps (*Vespula vulgaris*), grouse (*Dendragapus obscurus*), vole (*Microtus* spp.), northern goshawk (*Accipiter gentilis*), and marmot (*Marmota flaviventris*). Early stream restoration studies examined, creation of trout habitat using instream structures (Gard 1961a) and overhead cover (Butler and Hawthorne 1968). There was research on beavers (*Castor canadensis*) and their effects on riparian trees (Hall 1960) and trout (Gard 1961b). The Donner Ridge wildland fire and its aftermath spurred research on water chemistry in the Creek (Johnson and Needham 1966).

In the 1970s and 1980s, research shifted to forest management and wildlife, including reforestation, herbicide-treated plantations, snags and wildlife, furbearers, and postfire succession and impacts on bird habitat. There were also numerous publications on benthic macroinvertebrates in fens and Sagehen Creek (Erman 1973a, 1973b, 1981, 1986, 1989; Erman and Choteau 1979; Erman and Erman 1975, 1984, 1990, 1995; Hart 1978; Sheldon 1980). Biological studies during this time included studies of benthic macroinvertebrates, fish, and a wide variety of upland mammals, birds, plants, and invertebrates.

Research since the 1980s produced publications on benthic macroinvertebrates and fish as well as streamflow and sediment (Andrews and Erman 1986). From the late 1990s until present, there has been a large research effort on water and streams at SHEF: streamflow and snowpack (Coats 2010; Godsey et al. 2009, 2013), stream networks (Godsey and Kirchner 2014), in-stream large wood (Berg et al. 1998, 1999), springs and groundwater (Blumhagen and Clark 2008; Brumm et al. 2009; Manning et al. 2012; Rademacher et al. 2001, 2002, 2005), runoff chemistry (Gergans et al. 2011, Mast 2013), forest water use (Tague and Peng 2013), and meadow channel incision (Essaid and Hill 2014). Two snowmelt pans at Sagehen Creek Field Station (SCFS) have recorded since 2005. Recently, a series of climate change publications have drawn upon the long-term hydrologic dataset from SHEF (Godsey and Kirchner 2014, Hay et al. 2011, Meyers et al. 2010, Risley et al. 2011, Walker et al. 2011).

Research on effects of natural processes and forest management on nutrient fluxes has been conducted at SHEF and surrounding areas since 1966. Johnson et al. (1997, 1998a, 1998b, 2001) studied influences on nutrient fluxes of underlying geology and forest stand composition. Miller et al. (2005) and Loupe et al. (2009) investigated how fire suppression affects the soil litter layer and nutrients in overland flow. A number of studies have examined how wildland fires affect nutrient losses (Carroll et al. 2007; Johnson and Needham 1966; Johnson et al. 2012; Miller et al. 2006, 2010), and how forest fuel reduction treatments alter nutrient fluxes (Busse et al. 2013a, 2013b; Johnson et al. 2008, 2009, 2011; Loupe et al. 2009; Miller et al. 2010; Murphy et al. 2006a, 2006b; Roaldson et al. 2014). Wet and dry atmospheric deposition have been monitored at SHEF since 2001 as part of the NADP, or National Atmospheric Deposition Program (NADP 2019).

To address a USFS land management goal in the Sierra Nevada to reduce the risk of large, severe wildland fires (Gercke and Stewart 2006, Vaillant and Stephens 2009), a fuel reduction demonstration, called the Sagehen Project, consisting of forest thinning and prescribed fire treatments, will be implemented within SHEF (USDA FS 2013). This prototype will implement spatially placed land

area treatments designed to reduce landscape-scale fire risk using current best management practices (BMPs) for forest thinning and prescribed fire (North 2012, North et al. 2009). These management experiments will be monitored and studied to evaluate the treatments' effectiveness for reducing the risk of severe fires and for protecting ecosystem health, especially habitat for USFS-designated sensitive species, the Pacific marten (*Martes caurina*), northern goshawk, and California spotted owl (*Strix occidentalis occidentalis*). At this writing, planned treatments have begun and research and monitoring are underway.

Availability of publications and data—

SHEF's website (University of California, Berkeley 2003a) contains past bibliographies by category, and online copies of some SHEF-based Ph.D. and masters theses. Some hard copies of older thesis and original data are also available at Sagehen Creek Field Station.

The streamflow record (1953 to present), daily water temperature (1969 to present), and water quality (1968 to present) are available online (USDI GS station ID 10343500). Snow telemetry records (1978 to present) from the Independence Lake Snotel site and snow surveys (1937–1994) are available from the National Water and Climate Center (USDA NRCS 2017). Daily weather data collected since 1953 can be purchased from the National Centers for Environmental Information (USDC NOAA 2017). Daily climate data and snow depth and snowfall (1961 to present) are available online from the Western Regional Climate Center (Desert Research Institute 2017). Precipitation chemistry and dry deposition rates collected at sites CA99 and CA50 since 2001 are available online from the NADP (NADP 2019).

Biological Responses to Stream Nutrients N and P

Issues of Concern

The highest profile water quality issue on the east side of the northern Sierra Nevada is the decline of water clarity in Lake Tahoe, which is recognized by the U.S. Environmental Protection Agency (EPA) as a water body of national significance. When nitrogen (N) and phosphorous (P) enter this oligotrophic lake, they stimulate growth of algae and phytoplankton, which, together with suspended sediment, reduce water clarity. The deep-water portion of Lake Tahoe is listed under Section 303(d) of the Clean Water Act (United States Code 33, sections 1251-1387) for N, P, and suspended sediment. Lake Tahoe straddles the California-Nevada border, and each state has set its own water quality standards to sustain beneficial uses of noncontact water recreation and water of extraordinary ecologic or aesthetic value (LRWQCB 2010). The main sources of fine sediment and nutrients to the lake are from land development at the wildland-urban interface and

from upland forest runoff, including stream channel erosion, N fixation by riparian mountain alder, and atmospheric deposition (Coats et al. 1976, Jassby et al. 1999, Johnson et al. 1998a, Miller et al. 2010). SHEF lies 35 km northwest of Lake Tahoe and drains to the Truckee River downstream of the lake.

Wildland fires are important natural disturbances in the Sierra Nevada and can severely degrade water quality. Large-area, high-severity fires kill vegetation and consume surface organic matter, producing increased erosion, suspended sediments and nitrate (NO_3^-) leaching to surface water for several years after a burn. Fire suppression and logging in this region has produced forest fuel accumulations that increase the likelihood of extreme wildland fires, such as the 2013 Rim Fire that burned 1040 km² in the Sierra Nevada.

There is a concern that widespread application of fuel reduction treatments to reduce fire risk on large areas of the landscape might also affect water quality and future productivity of these forests. BMPs are often prescribed to minimize the impacts of forest fuel reduction treatments on water quality. The Lahontan Regional Water Quality Control Board (LRWQCB), for example, has required that when fuel reduction treatments are located within stream environment (riparian) zones in the Tahoe basin, timber pile burning for disposal of thinned trees is limited to no more than 15 percent of an acre (0.4 ha), unless the burn scars are in a significant stage of native vegetation recovery (LRWQCB 2014). SHEF is an experimental site where fuel management practices can be developed and tested.

Downstream from SHEF, a total maximum daily load (TMDL) for sediment in the Truckee River is calculated at the USGS Farad stream gage. The TMDL's purpose is to protect the natural value of instream aquatic life, especially early life stages, from habitat loss owing to siltation. Residential and recreational land development are a main source of controllable sediment, although nonurban areas also contribute sediment from dirt roads, graded ski runs, and legacy sites, such as poorly designed stream crossings, unstable stream channels and banks, and destabilized upland soils from past land uses (LRWQCB 2008). Forested basins with relatively little soil disturbance, such as SHEF, are probably minor sources of sediment.

Findings From Studies

Biological responses to stream nutrients have not been specifically studied at SHEF, but biological communities, especially fish and macroinvertebrates, have been investigated in SHEF streams in which ambient N and P stream water concentrations have been monitored. We first describe the studies on fish and then review research at SHEF on potential sources of stream N and P from forests and meadows, including effects of natural disturbances and land management.

Gard and Flittner (1974) reported elevational distribution and abundance of Sagehen Creek's major fish species: brook trout (*Salvelinus fontinalis* Mitchill), rainbow trout, brown trout (*Salmo trutta* L.), Piute sculpin (*Cottus beldingi* C. H. Eigenmann and R. S. Eigenmann), mountain whitefish (*Prosopium williamsoni* Girard), Tahoe sucker (*Catostomus tahoensis* T. N. Gill & D. S. Jordan), mountain sucker (*C. platyrhynchus* Cope), Lahontan redbreast (*Richardsonius egregius* Girard), and speckled dace (*Rhinichthys osculus* Girard). Diversity of fish was greater downstream. Fish species distribution by elevation was influenced by stream gradient, while the temporal abundance of fish was influenced by the timing and severity of floods. Erman (1986b) repeatedly sampled fish and channel parameters in the same stream reaches in the 1950s, 1970s, and 1980s. The fish distribution and channel cross sections did not change substantially over time, even with high- and low-flow years. Exceptions were in the downstream, impounded section of the creek where the Tahoe and mountain suckers declined and speckled dace, mountain whitefish, and brook trout disappeared, and the middle elevation of the creek where densities of brook trout and Paiute sculpin decreased. Erman et al. (1988) reported that large accumulations of snow restricted the channel capacity in winter and caused increased sediment transport during melt off, contributing to declines in brook trout and Paiute sculpin. Erman and Hawthorne (1976) found that rainbow trout preferentially spawned in an intermittent stream in a meadow compared to perennial tributaries, probably because of absence of competition from brook trout and early snowmelt runoff in the south-facing meadow. Snorkel surveys by Decker and Erman (1992) found all fish species preferred pool habitat, and maximum fish abundance was in mid-July, suggesting that previous electrofishing surveys were likely influenced by season and location of sampling.

Biogeochemical studies have examined N and P concentrations and fluxes in waterflows at SHEF. Mast (2013) reported mean NO_3^- -N concentration in Sagehen Creek was 0.09 mg/L. Mast and Clow (2000) reported concentrations and trends in ammonium (NH_4^+) and nitrite + nitrate in SHEF streams for 1985–1995. Gergans et al. (2011) studied NO_3^- , NH_4^+ , and P in rainwater, snowmelt, and ground-water collectors at SHEF and three other sites nearby (table 8.1). Atmospheric particulate NO_3^- and nitric acid vapor were measured in August 1994 at SHEF. Fluxes in deposition (0.3 kg N/ha/yr) and surface water leaching (0.4 kg N/ha/yr) were low compared to forests in the eastern United States and central Europe (Johnson et al. 1998b).

Studies of springs at SHEF found that groundwater chemistry influenced the chemical composition of stream water and may reflect past disturbances. The apparent groundwater age entering springs ranged from 5 to 40 years. Nitrate

Table 8.1—Mean concentration and standard deviation of inorganic nitrogen (NO_3^- - N = nitrate-nitrogen, NH_4^+ - N = ammonium-nitrogen), phosphate-phosphorus (PO_4^{3-} - P), and sulfate (SO_4^{2-}) in rainfall, snowmelt, groundwater, and runoff from Sagehen Experimental Forest and nearby Truckee (Miller et al. 2005), Tahoe Meadows (Loupe et al. 2017), and North Shore Lake Tahoe (Loupe et al. 2009)

	Mean concentration			
	NO_3^- - N	NH_4^+ - N	PO_4^{3-} - P	SO_4^{2-}
	----- mg/L -----			
Sagehen Experimental Watershed:				
Rainfall	0.22 ± 0.19	0.35 ± 0.46	0.08 ± 0.21	1.99 ± 0.56
Snowmelt	0.41 ± 0.48	1.09 ± 1.55	0.23 ± 0.29	2.14 ± 1.20
Groundwater:				
Ecotone	0.70 ± 0.56	7.38 ± 17.49	0.37 ± 0.69	2.74 ± 1.57
Wet meadow	0.53 ± 0.53	0.90 ± 1.58	0.07 ± 0.04	2.43 ± 1.21
Truckee, California:				
Snowmelt	—	—	0.09	—
Runoff	2.53	9.70	1.01	—
Tahoe Meadows, Nevada:				
Snowmelt	0.25	0.17	0.09	—
North Shore Lake Tahoe, California:				
Rainfall	0.82	0.28	0.15	3.21
Snowmelt	0.31	0.36	0.10	1.57

— = no data.

Source: Modified and reprinted from Gergans et al. 2011.

concentration exhibited a nonlinear relationship to the age of the springwater, with water entering springs after a short residence time in groundwater having little to no NO_3^- . Denitrification did not explain the low NO_3^- concentration, as these springs had high levels of dissolved oxygen. Older springwater had higher concentrations of NO_3^- , and the highest level was found in a spring receiving 30-year-old groundwater. Rademacher et al. (2001) observed high springwater NO_3^- in 1997 and 1999 and hypothesized that this peak may have reflected increased NO_3^- that entered groundwater three decades earlier when postfire soil nitrification was stimulated in the aftermath of the 1960 Donner Ridge Fire. Manning et al. (2012) reinterpreted the springwater age data using a binary mixing model with a young component (<1 year) flowing from the soil zone, and an older portion flowing from the fractured bedrock. The proportions of young and old water were related to partitioning between shallow runoff and groundwater recharge during snowmelt.

Surface runoff and water flowing through shallow soil can have nutrient levels higher than are typically found in SHEF streams, suggesting that soil may be a source of stream nutrients. Thick surface organic soil, called forest floor, accumulated during decades of fire exclusion, may prevent the conifer forest from recycling nutrients from surface soil to the canopy. Instead, nutrients released by forest floor decomposition may flow via surface runoff to streams. Gergans et al. (2011) studied a transect from the forest through a meadow to a tributary of Sagehen Creek to determine if N and P in overland flow through the forest's organic layer might affect stream water quality (table 8.1). They hypothesized that meadows would intercept and retain nutrients in overland flow that originated from the upland forest floor before they reached the stream. However, they found no significant difference in soil water nutrient concentrations between forest and meadow, although data trends suggested surface flows through the wet meadow may have loads of NO_3^- , NH_4^+ , and P greater than the upland. Their results indicated that wet meadows were not a sink for N and P that originated from the uplands and that meadows might possibly be an additional source of nutrients to streams.

In several east-side Sierra Nevada forests, Johnson et al. (2009) found a pattern of horizontal and vertical spatial distribution of soil carbon and nutrients owing to tree cover, litterfall, decomposition rates, and snow accumulation. In the horizontal dimension, N in the forest floor decreased sevenfold, from 1432 to 180 kg N/ha, between locations under tree canopies to those under gaps in the canopy. Under tree canopies, there were "islands of fertility" owing to greater soil organic matter and lower decomposition rates. Close to tree boles, where less snow accumulated in "tree wells," localized lack of summer moisture in forest floor caused slow decomposition and prevented rooting in the O horizon. In the Sierra Nevada, minimal winter soil freezing caused little root damage, unlike at Hubbard Brook Experimental Forest (see chapter 3), in New Hampshire, where reduced snow cover produced soil frost and winter root death. In the vertical dimension, N in the mineral horizon did not directly correspond to the overlying O horizon and varied threefold (632 to 1703 kg N/ha). Nitrogen uptake by trees occurred in underlying mineral soil horizons where tree roots were active.

Johnson et al. (1997, 1998a) compared N fluxes during snowmelt in forests at SHEF with Little Valley, another forest site in the eastern Sierra Nevada. SHEF had high NO_3^- concentrations in snowmelt (2 to 8.5 mg NO_3^- -N/L) that penetrated the soil and produced a NO_3^- pulse in the stream water (0.04 to 3.4 mg NO_3^- -N/L). By comparison, at Little Valley, NO_3^- that was released from melting snowpack did not appear as a NO_3^- pulse in soil water or in stream water (Johnson et al. 2001). The investigators' explanation was that snowmelt at SHEF occurred early in the season,

when trees and soil biota were probably dormant and unable to take up the NO_3^- . By comparison, at Little Valley, NO_3^- release from snowpack occurred later in snowmelt, when plants and soil microbes were active and could take up NO_3^- rapidly. As an alternate explanation, they suggested biotic uptake of NO_3^- might be P limited in the SHEF forest, but not at Little Valley, because soils at SHEF were low in P compared to Little Valley.

Other Factors Relevant to Stream Nutrients N and P

Long-term monitoring at SHEF has produced datasets of several environmental factors that may influence biological responses to stream N and P. For example, streamflow, water quality, and stream water temperature have been monitored in SHEF streams for many years. In addition, a number of parameters related to atmospheric influences have also been monitored, including air temperature, precipitation amount, solar insolation, and snow depth and water content, and the chemical composition of wet and dry deposition. These long-term databases provide a useful environmental context for interpreting results of experiments at this site.

Reference Watersheds

SHEF does not have reference watersheds that are explicitly set aside for minimal human disturbance, although SHEF has been used as a de facto reference watershed for sediment loading in a nearby drainage, following the EPA protocol for reference watershed comparisons (Bullard et al. 2002). The SHEF basin has had relatively little disturbance, with few roads and low-intensity forest management and recreational use in recent decades. However, without a formal commitment to manage a reference basin within SHEF for minimal onsite human disturbance, the future value of SHEF for research and regulatory purposes might be compromised. There is a risk that future management actions might leave no monitored subbasin within SHEF that could serve as an unmanaged reference.

Cross-Site and Regional Studies

Mast (2013) compared stream and precipitation chemistry trends for 15 relatively undisturbed hydrologic benchmark sites across the United States, including SHEF. Sagehen Creek did not show any trend in annual mean stream water NO_3^- concentration from 1990 to 2010. The precipitation chemistry at SHEF showed a significant decline in hydrogen ion concentration and NO_3^- , and a nonsignificant increase in NH_4^+ , between 1990 and 2010. The Air Resources Board (2006) compared wet deposition of N at SHEF with other sites in the Lake Tahoe Basin, and Mast (2013) reported that N deposition in wet precipitation at the nearby Independence Ridge NADP station had decreased significantly from 1990 to 2010.

Several studies have included SHEF in comparisons of internal nutrient fluxes in forest ecosystems across the United States. Compared to humid forests, fluxes of N at SHEF are extremely low. Within SHEF, postfire N fixation by shrubs dominate N balances by an order of magnitude compared to fluxes via solution phase (Johnson et al. 1997, 2009) (fig. 8.2). Extractable P content in SHEF soil (0.2 kg P/ha) was the lowest of 16 forests across the United States (Johnson et al. 1997). A comparison of abiotic and biotic processes affecting N retention among forests in SHEF, Little Valley, Washington, Tennessee, and North Carolina found that SHEF and Little

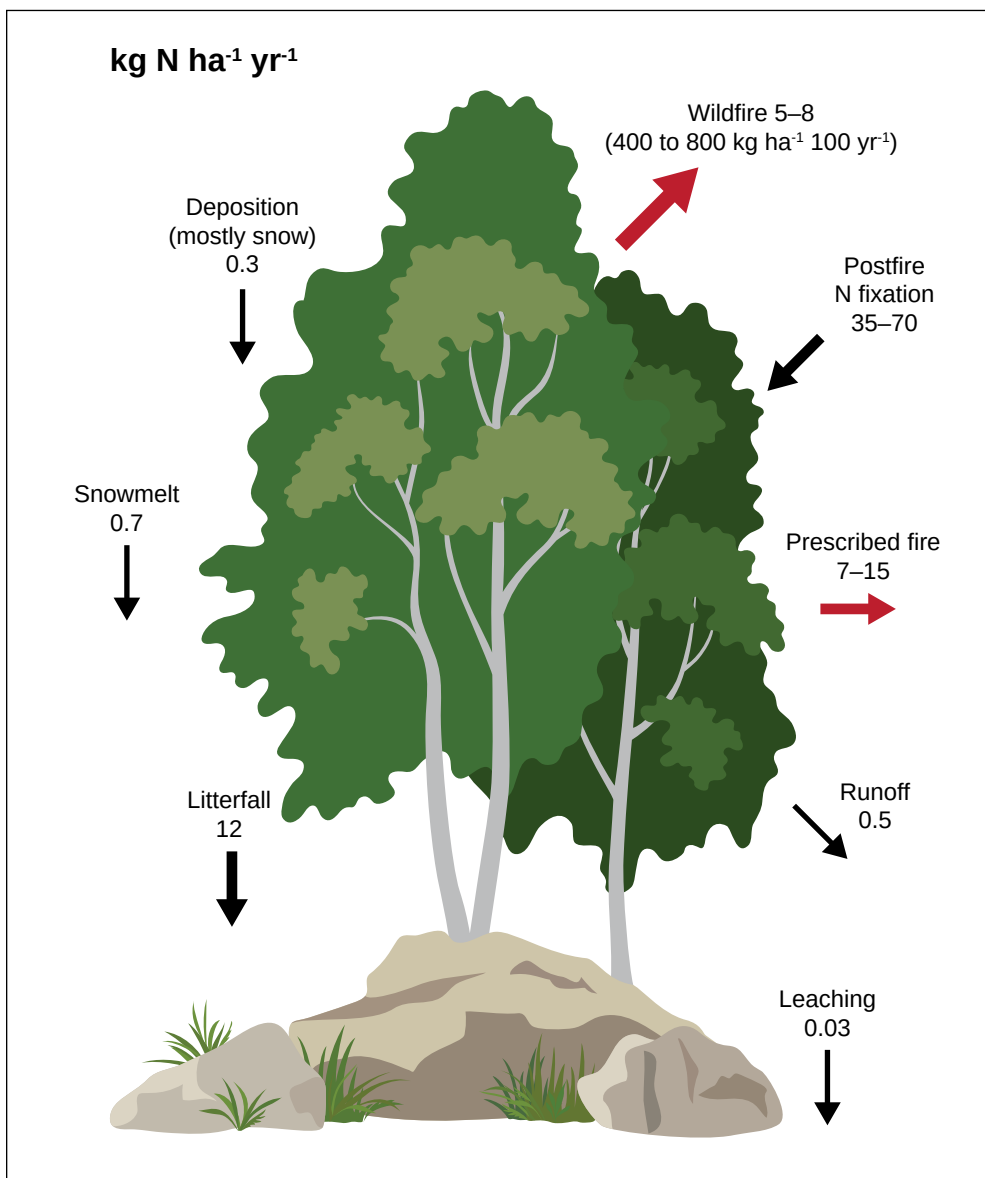


Figure 8.2—Fluxes of nitrogen (N) with wildland fire and prescribed fire compared to fluxes from atmospheric deposition, snowmelt, litterfall, leaching, and runoff. Redrawn from Johnson et al. (2009: 2249–2260).

Valley had low N pools in soils compared to the other sites, possibly owing to low N deposition rates and loss of N from historically recurring fires at these Sierra Nevada sites (Johnson et al. 2000).

Dose-Response Studies

No dose-response studies have been conducted at SHEF.

Responses to Management and Natural Disturbances

Several studies at SHEF and surrounding areas have examined the potential effects of natural disturbances and management actions on water quality and beneficial uses of water.

Using studies along a 10-km reach of Sagehen Creek, Gard and Seegrist (1972) found that supplemental hatchery fish were not required to sustain angler harvest because recruitment could replace losses. The researchers recommended two strategies to produce large trout: construct low dams, similar to beaver dams, and impose limits on angler take.

Miller et al. (2010) estimated that the past 130 years of fire suppression has resulted in a net accumulation of N and P in the soil and plant biomass compared to historical levels. Current conditions contrasted with the low-nutrient levels of historical forest stands that experienced more frequent, but lower severity, fires. The recent accumulation of litter and nutrients in current forests may lead to increased nutrients in runoff to Lake Tahoe and affect its oligotrophic status. They estimated that, over the long run, prescribed fire and forest thinning could potentially reduce nutrient release to downstream waters compared with current-day forests.

Following the Donner Ridge Fire, Johnson and Needham (1966) found that stream water chemistry was not affected. They theorized that soluble cations leached from ash did not wash into streams, but were apparently absorbed in the exchange complex within the soil. They attributed this behavior to a combination of light rainfall following the fire and the highly acidic, permeable soils.

Wildland fires affect soils by volatilizing N from burned organic matter and mobilizing NH_4^+ from organic to mineral soils. Johnson et al. (2012) compared the soil carbon and nutrient content of a SHEF site burned in the Donner Ridge wildland fire with a nearby site, Little Valley, also burned in the 1960 fire. Their goal was to see if the soil parent material, andesitic at SHEF, and granitic at Little Valley, had mediated the effects of postfire vegetation on soil chemistry 50 years after the fire. In the previously burned area at SHEF, the carbon:nitrogen (C:N) ratio, and extractable P, were lower than in unburned forest. In contrast, at Little Valley, the burned area had soil-extractable P that was equal or greater than that of unburned forest. Comparing the two sites, they concluded that soil parent material mediates the effects of postfire vegetation on soil chemistry.

Studies of the 2002 Gondola Fire, in the South Lake Tahoe watershed, quantified nutrient losses during and after fire. Postfire, there was less runoff of water from the burned area compared to an unburned area probably owing to the creation of a layer of wettable soil (Miller et al. 2006). Although the NO_3^- and NH_4^+ concentrations in the interflow through soil litter tended to be higher in the burned areas, the only significant difference was for orthophosphate (PO_4^{3-}) 1 year postfire (Miller et al. 2006). Miller et al. (2010) combined results of Miller et al. (2006) with Loupe et al. (2009) to estimate that annual discharge loads of mineral N and PO_4^{3-} following the Gondola Fire were double the levels prefire: 14 kg N/ha/yr vs. 7 kg N/ha/yr for mineral N, and 2 kg P/ha/yr vs. 1 kg P/ha/yr for PO_4^{3-} . In another study, Johnson et al. (2009) reported that leaching of N for 2 years following the Gondola Fire was tenfold greater than on an unburned site nearby, but the increase in N leaching (-19 kg N/ha) was only 4 percent of estimated N losses by volatilization during the fire. Average N loss from tree biomass caused by fire was large (-191 $\pm$ 72 kg N/ha), as was loss from the forest floor (-142 $\pm$ 48 kg N/ha) and mineral soil (-92 $\pm$ 126 kg N/ha), predominantly owing to volatilization (Johnson et al. 2009). Carroll et al. (2007) estimated that a single postfire erosion event after the Gondola Fire, from an intense rainstorm, caused a loss of 291 kg N/ha presumably in sediment.

In a study conducted 5 years after the Gondola Fire, Miller et al. (2013) found that N in soil solution had returned to prefire levels and that the effects of the wild-fire on nutrients and water quality were influenced by postfire weather. A wet year after a wildland fire, by leaching more N from soils, could cause a greater impact on water quality than a dry year.

Management of forests to decrease wildland fire risk with prescribed fire and forest thinning can potentially affect water quality, although effects are generally less than from severe wildland fires. Loupe et al. (2009) studied the impacts on runoff and nutrient concentrations of four different forest thinning and prescribed fire treatments: (1) unharvested and unburned, (2) harvested and burned, (3) harvested only, and (4) burned only. They found that harvested-only and burned-only treatments increased NO_3^- in runoff more than did combined harvested and burned treatments. However, although discharge loads of NO_3^- increased postthinning and postburning in interflow and overland flow, the increased loads were minimal compared with background levels.

To place nutrient effects of forest fuels reduction in a longer term perspective, Johnson et al. (2008) compared estimated ecosystem losses from forest fuel reduction treatments with ecosystem inputs of nutrients from atmospheric deposition over a fuels treatment return cycle. They combined pretreatment nutrient capital and the atmospheric deposition rates from SHEF with estimates of nutrient removals for the following forest fuels reduction treatments: whole-tree removal with prescribed fire,

cut-to-length log removal with prescribed fire, and prescribed fire alone (Murphy et al. 2006b). Among the three treatments, the loss of N as a percentage of the ecosystem nutrient capital was not significantly different, and nutrient losses represented less than 5 percent of N capital, regardless of treatment. However, the loss of P in the whole-tree removal was 20 to 22 percent greater than in the cut-to-length and prescribed fire-only treatments. If atmospheric deposition were the only ecosystem input of N, they estimated it would take 281, 414, and 663 years to replace the N removed in the prescribed fire-only, cut-to-length, and whole-tree treatments, respectively. Practical fuel treatment cycles would likely be considerably shorter than those nutrient replenishment times. Growth of snowbrush, an N-fixing shrub, following a wildland fire replaced N more quickly than atmospheric deposition. However, snowbrush may not always be desirable because, without management to control it, dense snowbrush may competitively exclude trees for decades.

Total soil N constituted about 90 percent of ecosystem capital, but only a small portion is available to plants, while P capital, based on conventionally extracted soil P, probably underestimated P available from andesitic soils (Johnson et al. 2008). Johnson et al. (2009) concluded that N is the nutrient whose removal by harvesting and burning was most likely to be limiting in the future under these fuels reduction management regimes, and that repeated forest fuel reduction treatments on short-time rotations could lead to N deficiency. However, this management-induced, N-limited condition might resemble what probably existed naturally in Sierra Nevada forests prior to settlement by nonindigenous people, when wildland fires were more frequent.

Management practices to reduce forest fuels often include thinning of overstocked stands and onsite disposal of the thinned material. An important question for the LRWQCB is, What effect would burning piles of thinned forest material have on soil and water quality? Investigating that question, Johnson et al. (2011) collected ash and soils from burn scars left by slash disposal piles of various sizes (8 to 15 m²) in forest and meadow sites at Little Valley. Larger piles had decreased soil total C and N toward the burn scar center, indicating high burn temperatures, but concentrations were unaffected in the center of smaller piles. In the meadow, they found soil solution NO₃⁻ in burn scars was higher than in upland forest scars. Average NO₃⁻ concentration in the soil solution in meadow burn scars was 6.5 mg NO₃⁻-N/L, and maximum concentration was 9.5 mg NO₃⁻-N/L (Johnson et al. 2011). They concluded that burning small piles produced less effect on soil nutrients than burning large piles, that burning slash piles in upland areas had more effect on soil nutrients than on water quality, and that burning slash in riparian or meadow areas could potentially affect both soil and water quality (Johnson et

al. 2011). Hatchett et al. (2006) reported that reducing forest fuels by mechanical grinding (mastication) of vegetation had minimal effect on soil erosion. The studies by Johnson et al. (2011) and Hatchett et al. (2006) were part of the scientific basis LRWQCB used to develop current BMPs for fuel reduction treatments (LRWQCB 2014).

Busse et al. (2013b) also studied effects of burn pile size and fuel material diameter on soil and water quality in the Lake Tahoe Basin. They found that the size of the pile (average area 7 m², maximum area 64 m²) did not predict soil heating. Rather, if the pile contained more than 40 percent by mass of wood with diameter greater than 23 cm, there were high soil temperatures during the burn that could volatilize soil C and N. They found that burn piles had no significant impact on soil or soil water quality, if they were composed primarily of small-diameter wood, occupied less than 30 percent of the ground surface, and were extinguished with water within 8 hours after ignition. Busse et al. (2013a) found low nutrient fluxes in overland flow following pile burning that declined with distance down slope, although robustness of their results was limited by a small sample size.

Hubbert et al. (2015) further tested the impact of pile burning on soil water repellency, and nutrient concentrations in runoff in the Lake Tahoe Basin. They found that pile burning increased soil water repellency but had no significant effect on nutrient runoff. They reported that levels of NO₃⁻ in runoff remained below EPA standards for water quality, and concluded that burning close to streams may not affect water quality. Further study will be needed to resolve differences between the findings of Hubbert et al. (2015) and Johnson et al. (2011) about how much burn scars affect soil water NO₃⁻ in riparian and meadow areas.

Reliability and Limitations of Findings

The research results and environmental datasets from SHEF may apply to other east-side forests in the central and northern Sierra Nevada where atmospheric deposition of N is low and underlying geology is comparable. Areas with high atmospheric deposition of N, such as the southern Sierra Nevada, may have different N dynamics. Areas that lack porous volcanic bedrock and a large groundwater reservoir may have different hydrological and stream chemical characteristics. Caution should be used, for example, when applying results from SHEF to the Lake Tahoe Basin, which largely lacks porous bedrock. When applying SHEF results to areas with different land use, geology, or climate, or for uses that require a high degree of accuracy, we suggest validation experiments or monitoring to test how well SHEF datasets predict local conditions.

Research Needs

The highest priority research need of the regional water quality community related to N and P that could be filled at SHEF is, How effective are current BMPs for forest fuel reduction treatments, compared to alternatives, for protecting stream water quality from added loads of nutrients and suspended sediment? Answering this question would be useful to the water quality regulatory community because it would give them science-based information to evaluate the effectiveness of current BMPs for fuels reduction compared with alternative practices for protecting beneficial uses of water in the northern Sierra Nevada, including the Lake Tahoe Basin.

The fuels reduction treatments that will be implemented at SHEF in the Sagehen Project provide potential opportunities to investigate effectiveness of current BMPs for fuel reduction treatments, including forest thinning and prescribed burning. Future research of most immediate use to regulatory agencies would be studies to examine potential effects on water quality of slash disposal burn piles using current BMPs. Of particular interest would be the water quality outcomes of performance-based measures of vegetation recovery, and the effect of locating piles in upland forest, meadow, and stream environment (riparian) zones. However, the Sagehen Project currently only plans limited studies of treatment effects on water, such as routine monitoring of main-stem Sagehen Creek for water quality, streamflow at SHEF gaging stations, and a study to evaluate water yield changes in response to treatments (Hogue 2014). Studies of effects of slash disposal burn scars on water quality are not currently planned and would require additional resources.

Water quality regulatory agencies might gain added value if research at SHEF investigated the effectiveness of alternative fuel reduction practices along with the planned treatments that follow current BMPs. Measuring effectiveness of treatments might take several years. If the outcomes of current practices prove to be lacking in some respect, simultaneously testing alternatives might save regulators the additional years to see if alternatives would do better. However, only conventional fuel reduction treatments, following current BMPs, are planned in the Sagehen Project, so implementing any alternative practices and studies to measure their effectiveness would require additional resources.

Another research area of potential interest to regulators, although of lower priority, would be investigating how forest floor and underlying water-repellant soils in Sierra Nevada forests interact to produce N and P observed in interflow and what mechanisms transform nutrients in interflow into stream water concentration and fluxes.

Potential Utility to Water Quality Regulatory Agencies

Existing long-term datasets from SHEF on streamflow, snowfall, precipitation, and stream nutrients N and P may be useful to water quality regulatory agencies for representing these nutrients in relatively undisturbed headwater basins for purposes such as developing water quality standards and for TMDL modeling. Research results from previous, detailed studies at SHEF on the potential effects on water quality of management practices, such as burning of logging slash, could be useful to the regulatory community for evaluating and developing guidelines for forest management practices such as BMPs and permitting.

Key points:

- SHEF has low stream water concentrations of N and P as is typical in undisturbed headwaters in the region.
- Snowmelt drives streamflow, and groundwater drives stream water chemistry.
- Meadows did not act as sinks for nutrients carried from upland forests in surface flows.
- Wildland fires remove N from these forests, and postfire fixation by shrubs restores N.
- There is uncertainty about the effects of slash burning on water quality in meadows and riparian zones during fuel reduction treatments.
- The Sagehen Project fuel reduction treatments offer opportunities to study the impacts of forest slash pile burning on vegetation recovery and nutrients in soil and runoff if added resources became available.
- Valuable information might be gained if alternative fuel treatments were tested at SHEF.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

An issue of concern is whether land management actions that disturb vegetation or soils, such as forest fuel reduction treatments, might affect perennial springs and spring-fed wetlands called fens. In eastern Sierra Nevada basins, these water bodies are heavily dependent on groundwater, which controls waterflow temperature and chemistry in springs and fens. Any disruption by forest management of these aquatic conditions might degrade the rich biological diversity in the region's springs and fens.

Where it occurs, hardrock mineral mining and exploration has sometimes degraded water quality in basins of the Sierra Nevada. High concentrations of

sulfate (SO_4^{2-}), iron, manganese, and toxic heavy metals in drainage from mines and spoil disposal can affect beneficial uses in surface waters, such as drinking water, fish habitat, and water-contact recreation. The Sagehen basin has had no significant mining activity so its streams may serve as a benchmark for stream water quality in the absence of mining.

Findings From Studies

Studies at SHEF have investigated the important contribution of spring habitat to macroinvertebrate diversity and abundance. Erman and Erman (1990, 1995) studied the alkalinity, calcium (Ca^{2+}), and magnesium (Mg^{2+}) chemistry of springs at SHEF and in two nearby forests and found that the diversity of caddisflies is a function of long-term spring permanence. These studies used flow variation among springs, correlation of ions with flow, and variations in flow over time as surrogate measures of spring permanence, and their results were confirmed by more recent measurements of groundwater age by Rademacher et al. (2001, 2005).

Spring-fed streams and fens support a high diversity of aquatic macroinvertebrates. More than half of the caddisfly species in Sagehen Creek inhabited springs during all or part of their aquatic life cycle, and nine were restricted to spring habitat. Approximately 75 percent of caddisfly species composition and richness were unique to each spring, and two springs, only 1.6 km apart, shared only 28 percent of species (Erman and Erman 1990). The constant temperature in springs may provide a narrow range of habitat to which species recently evolved, or, alternatively, these species may be relics of an earlier climatic period when they were more widely distributed. Some caddisfly species only mate close to a spring because they fly only a short distance as emergent adults. Thus, springs act as habitat islands within the forested landscape, and theories of island biogeography may apply to species colonization and extinction (Erman 2015). In addition, springs discharge aquatic fine particulate organic matter in substantial amounts (5 to 20 g m^2/yr), which is a key food source for macroinvertebrates in the creek (Erman and Chouteau 1979).

Rademacher et al. (2005) studied the influence of groundwater on springs and stream chemical composition at SHEF. Water entering springs after a longer residence time in groundwater had water chemistry dominated by rock weathering products such as high cation concentration, pH, sodium (Na^+), and Ca^{2+} (Rademacher et al. 2001). Rademacher et al. (2005) determined the age of groundwater flowing into the creek using chlorofluorocarbon apparent age and the chemical composition of groundwater. During baseflow, when the streamflow was low, the average residence time of groundwater was 28 years, based on the relationship between chlorofluorocarbon CFC-11 and Ca^{2+} . In contrast, during snowmelt periods, the average age of groundwater discharging to the creek was 15 years, based on the relationship between CFC-11 and the ratio of chloride (Cl^-) to Ca^{2+} .

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

Long-term databases of environmental factors monitored at SHEF that might influence biological responses to stream nutrients other than N and P are the same as those reported in the section on “Biological Responses to Stream Nutrients N and P.”

Reference Watersheds

Long-term monitoring of nutrients other than N and P has been done on the main stem of Sagehen Creek, which has been considered a de facto reference reach (Bullard et al. 2002), but no reference basin within SHEF is formally set aside to be managed for minimal onsite human disturbance in the future.

Cross-Site and Regional Studies

Mast and Clow (2000) reported concentrations and trends in Ca^{2+} , Mg^{2+} , Na^+ , potassium (K^+), SO_4^{2-} , Cl^- , and silica (SiO_4) in SHEF streams (1985–1995) and compared them to other western streams. Mast (2013) included SHEF monitoring of nutrients other than N and P in his comparison of stream and precipitation chemistry trends among 15 hydrologic benchmark stations across the United States. In SHEF stream water, the Ca^{2+} plus Mg^{2+} declined significantly from 1970 to 2010, but not during the shorter 1990–2010 period. The precipitation chemistry at SHEF showed a significant decline in hydrogen ion concentration, acid neutralizing capacity, and Ca^{2+} plus Mg^{2+} and a nonsignificant decrease in SO_4^{2-} between 1990 and 2010. All of the other stations reviewed, except SHEF and a site in Nebraska, showed significant declines in SO_4^{2-} after passage of the 1990 Clean Air Act Amendments.

Two studies illustrated the relationships between stream chemistry and flow, and snowpack and streamflow that have implications for water quality and biological responses. Godsey et al. (2009) studied the chemical composition of Sagehen Creek in relation to discharge and compared results to 58 other USGS benchmark stations in relatively undisturbed watersheds. They studied solutes produced by mineral weathering: Ca^{2+} , Mg^{2+} , Na^+ , and SiO_4 . Sagehen Creek had a power law relationship between solutes and stream discharge for both single events and on an interannual basis (fig. 8.3). They described the relative constancy of concentrations across a large range of stream discharge at SHEF as a chemostatic relationship with discharge. Rademacher et al. (2005) suggested a mechanism to explain this behavior at SHEF: the discharge of “old” groundwater into streams during high-flow snowmelt periods maintained solute flux in proportion to water flux.

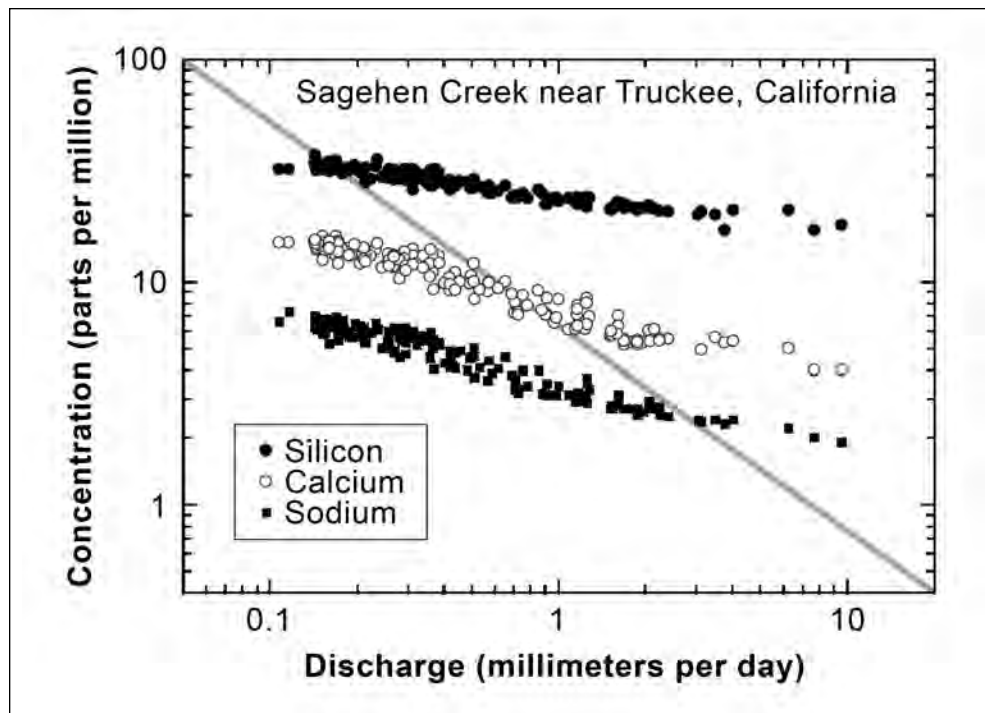


Figure 8.3—Concentration in Sagehen Creek of solutes produced by mineral weathering in relation to discharge. Concentrations based on dilution of fixed weathering fluxes would follow the gray line on the log plot, but the data follow a more chemostatic pattern with a slope closer to zero (Godsey et al. 2009: 1844–1864).

Godsey et al. (2013) investigated potential effects of different climate change scenarios on the relationship between snowpack and streamflow at SHEF and seven other sites in the Sierra Nevada. They found that Sagehen Creek exhibits a “memory effect” in which low flows reflect both the current snowpack and the previous year’s snowpacks, likely an effect of groundwater storage in the basin. With climate warming, snowpack volume in the Sierra Nevada is predicted to decline by 40 to 90 percent over the next century, and regionwide, for every 10 percent decrease in peak snow-water equivalent, the annual minimum flow, on average, is expected to decrease by 9 to 22 percent. However, using a hydrologic model, they estimated that at SHEF, a 10 percent decrease in peak snow-water equivalent would result in only a 1 to 8 percent decrease in summer low streamflows. As climate warms and winter precipitation shifts from snow to rain, streamflow in watersheds with porous volcanic bedrock, such as SHEF, may be buffered against the loss of snowpack because its large reserve of groundwater can store recharge during the fall and winter to sustain flow during dry seasons.

Responses to Management and Natural Disturbances

Studies have examined effects of management and natural disturbances on biological communities in SHEF streams and fens unrelated to N and P. Berg et al. (1999) assessed the effects of wildland fire on instream wood at Bradenaugh Creek compared to the unburned Sagehen Creek. They estimated that wildland fire resulted in the loss of 45 percent of instream C storage, which was 1.5 to 2.5 times the loss of terrestrial C storage. Because instream large wood also forms critical habitat for fish, its loss during wildland fires may adversely affect stream biota. Gard (1961b) found that since the reintroduction of beavers (*Castor canadensis*), water temperature, dissolved oxygen, and alkalinity in the stream had changed as a result of reestablished beaver ponds. Ponds also produced big trout by creating favorable habitat. Bartolome et al. (1990) studied peat accumulations in Sagehen fens and found that fens were persistent features with dynamic pine invasions suggesting that management of short-term pine invasion was not needed to preserve fen ecosystems. The large body of research on benthic macroinvertebrates and fens at SHEF has served as a science base for fen conservation in USFS land management and planning (Erman 1973a, 1973b, 1981, 1986b, 1989; Erman and Choteau 1979; Erman and Erman 1975, 1984, 1990, 1995; Hart 1979; Sheldon 1980).

Reliability and Limitations of Findings

Findings from SHEF can probably be applied to other watersheds in the Sierra Nevada that have similar climate, land uses, rates of atmospheric deposition, and geology. Where such characteristics differ widely from SHEF, or where a high degree of accuracy is required, validation experiments of monitoring could be conducted to test how well SHEF datasets predict local conditions.

Research Needs

The highest priority research need of the regulatory community that might be filled at SHEF related to nutrients other than N and P is to understand how water quality, waterflows, and diverse aquatic macroinvertebrate communities in springs and fens are affected by forest fuel reduction practices, such as thinning, prescribed fire, and pile burning. Filling this need at SHEF might be useful to regulators by providing them with a scientific basis for developing management guidelines for protecting sensitive springs and fens during forest fuels management operations.

The Sagehen Project fuel reduction treatments of forest thinning and prescribed burning might provide opportunities to investigate posttreatment effects on springs and fens by monitoring macroinvertebrate diversity and abundance, with a focus on caddisflies, along with effects on critical habitat features, including springwater

chemistry, flow, temperature, and fine particulate organic material. Previous studies of SHEF springs, such as Erman and Erman (1984, 1990, 1995), might serve as a surrogate for pretreatment monitoring. Additionally, the existing long-term SHEF streamflow record, studies of the dependence of spring waterflows on groundwater, and results of studies on effects of fuel reduction treatments on soil water nutrients might be used to develop models of how forest treatments are likely to affect spring water quality and invertebrate habitat. However, as currently planned, the Sagehen Project does not include any studies of treatment effects on springs or fens, so such studies would require additional resources.

Potential Utility to Water Quality Regulatory Agencies

Existing research results from past studies at SHEF on the highly diverse macroinvertebrate communities in perennial springs and fens and the dynamics of groundwater that control the physical and chemical habitat in these waterbodies may be useful to the regulatory community for developing guidelines for protecting these aquatic communities of high ecological value. SHEF research results might also help regulators anticipate climate change impacts on waterflows from Sierra Nevada headwater basins. For example, findings by Godsey and Kirchner (2014) that underlying porous bedrock could buffer the SHEF basin against low summer flows as climate warms, might be applied to other Sierra Nevada drainages with similar geology.

Key points:

- Springs provide important habitats, supporting a high diversity of endemic macroinvertebrates.
- Groundwater controls on chemistry of springs, primarily related to nutrients other than N and P, exert strong influences on stream water quality.
- Concentrations of mineral weathering products in streams show little variation compared to changes in discharge.
- A research need for the regulatory community that might be filled at SHEF is to better understand how fuels treatments affect macroinvertebrates in springs and fens.
- The Sagehen Project treatments might offer opportunities to fill that need, but additional resources would be required.
- Existing SHEF science findings might be used by regulatory agencies to develop hydrochemical models to predict how flow and chemistry in springs and streams respond to climate change.

Overview and Synthesis

Biological responses specifically to stream nutrients have not been investigated at SHEF, but biological communities, especially fish and macroinvertebrates, have been studied in SHEF streams in which ambient stream water nutrient concentrations have been monitored. SHEF is a headwater basin where streamflow is mainly driven by snowmelt and nutrient levels are low. Water quality in the basin is mainly controlled by groundwater emerging in springs, but wildland fires, when they occur, can have large effects on stream water N and sediment. Extensive research has been conducted at SHEF on fish, benthic macroinvertebrates, wildlife, and biogeochemical cycles. Past studies show high spatial variability in forest soil nutrients depending on forest cover and soil parent material (Johnson et al. 1997, 1998a, 2009). There were pulses of soil water NO_3^- recorded in interflow through the O layer (Loupe et al. 2009, Miller et al. 2005) that may play an important role in nutrient loading to streams, although the detailed mechanisms are not fully understood (table 8.2). Further studies could refine the understanding of how nutrients in interflow contribute to stream loading, and how geologic differences and soil water repellency influence nutrient loads and runoff.

Loss of N by volatilization during wildland fires is large compared to leaching or decomposition. The Gondola Fire provided an opportunity to study pre- and postfire nutrient levels and improved understanding of nutrient fluxes over time periods ranging from a single storm, to the first 5 years postfire. A study 52 years after the Donner Fire suggested that soil parent material mediated postfire vegetation growth and soil chemistry. Combining these postfire studies with research on spring water age and climate change raises some interesting cross-disciplinary connections. One possible connection is that the concentration of NO_3^- in spring water may reflect past wildland fires that occurred several decades ago, as suggested by Rademacher et al. (2005). Another potential cross-disciplinary connection might be that soil water repellency that was found after the Gondola Fire (Miller et al. 2006) may alter groundwater recharge and leave a record that is detectable in spring water age (Manning et al. 2012). Additionally, Godsey and Kirchner (2014) found that the shift from snow to rain with climate change would lead to decreased summer flows in Sierra Nevada basins, but that porous bedrock would moderate this effect at SHEF. Better understanding of the relationship between spring water as a function of groundwater recharge from snowmelt and natural or anthropogenic forest disturbances might provide insights on basin-scale controls of stream hydrology and water quality.

Table 8.2—Nitrogen (N) and phosphorous (P) forms recorded in runoff from forest floor and overland flow from December 2001 to July 2003 near Truckee, California, and South Lake Tahoe, Nevada

	Total runoff (L) 12/01–07 /03	Average concentration (mg/L)			Maximum concentration (mg/L)		
		NH ₄ ⁺ -N	NO ₃ ⁻ -N	P0 ₄ -P	NH ₄ ⁺ -N	NO ₃ ⁻ -N	PO ₄ ³⁻ P
Truckee							
P1	5.80	4.03	3.97	0.06	23.60	21.90	0.25
P3	50.44	2.52	1.49	0.26	12.11	11.84	0.09
P5	19.33	2.17	2.77	0.13	5.8	8.55	0.19
P7	33.56	30.83	6.56	2.85	87.28	95.47	13.12
P8	5.51	3.56	8.51	0.21	23.49	31.30	0.58
P9	45.45	5.24	2.69	0.72	21.22	16.47	4.55
P23	16.75	4.70	1.63	1.68	36.20	12.10	11.80
P25	23.10	2.75	2.17	0.09	8.04	14.38	0.23
Average	24.99	6.98	3.72	0.75	27.22	26.50	3.95
Standard deviation	16.86	9.70	2.53	1.01	26.20	28.77	5.46
South Lake Tahoe							
P1	25.61	0.12	0.80	0.19	0.40	3.35	0.36
P2	76.14	0.18	0.43	0.10	0.58	3.79	0.31
P3	42.62	0.58	2.32	0.25	2.34	9.37	0.71
P14	29.69	5.16	2.01	0.83	61.10	22.15	4.27
Average	43.52	1.51	1.39	0.34	16.10	9.67	1.41
Standard deviation	22.93	2.44	0.92	0.33	30.01	8.76	1.91

NH₄⁺-N = ammonium-nitrogen, NO₃⁻-N = nitrate-nitrogen, PO₄³⁻-P = phosphate-phosphorus.

Source: Reprinted from Miller et al. 2005: 3–17.

Suppression of wildland fires and only minor forest management operations in SHEF for more than 50 years have led to an accumulation of forest fuels. The forest thinning and prescribed fire treatments to reduce fuels that are planned in the Sagehen Project may provide opportunities to study water quality and quantity impacts of the treatments. Based on past studies, it is predicted that the impact of the forest treatments on stream water N will be small. However, past research has not settled the question of whether NO₃⁻ levels in subsurface flows beneath burn piles in meadows will affect stream water quality. Studies have found that meadows did not act as a sink for nutrients and may be a contributing source, but investigations of effects of burn scars on water quality have not been definitive. Applying results of past studies at SHEF might be useful for developing regulations and management guidelines for maintaining the clarity of Lake Tahoe and meeting TMDL standards in rivers. However, caution should be used when extrapolating from SHEF to other watersheds. For example, different underlying geology, and groundwater dynamics in the Lake Tahoe Basin might produce basin-scale water quality responses that differ from those at SHEF.

The research on springs, snowpack, and streamflow found that groundwater at SHEF played a strong role in stream water chemistry. Older springs contribute more NO_3^- to the creek, and the solute flux in the creek exhibits a chemostatic response, changing relatively little with discharge. SHEF is also likely buffered from climate warming owing to its porous volcanic bedrock, which can potentially store rain in the fall and winter as groundwater that then maintain low flows in the summer. These strong relationships between groundwater and stream water help explain the water chemistry and low nutrient concentrations in SHEF streams. Biological studies on benthic macroinvertebrates, especially caddisflies, in springs and fens at SHEF indicate the importance of these stable spring water habitats as refuges of biodiversity.

The highest priority research needs of the regional water quality regulatory community that might be filled at SHEF are research on surface water quality in runoff from slash pile burns in meadow and riparian areas, including effects of vegetation recovery, and potential impacts of forest fuels reduction treatments on springs and fens and their diverse macroinvertebrate communities. As currently planned, the Sagehen Project will implement fuel reduction treatments following current BMPs, but that does not include detailed studies that would address the research needs of the water quality regulatory community, nor any alternatives treatments to compare with current practices. Studies that would pursue regulatory agency priority science needs at SHEF would require additional resources. The existing body of research results and long-term datasets from SHEF are readily available for use by the water quality regulatory community on topics such as streamflow, geochemistry, fish and aquatic macroinvertebrates, nutrient fluxes, and potential effects on water quality of wildland fire and forest management in forests on the east side of the Sierra Nevada.

Key points:

- Biological responses to stream nutrients have not been investigated at SHEF, but a wide variety of other water quality related issues have been studied.
- Streams are low in nutrients, but surface runoff and soil water can be elevated, especially where soil has been disturbed by fire.
- Wildland fires have major effects on forest nutrient pools and stream loading.
- Fuels treatments to reduce fire risk probably reduce nutrient loads to streams in the long run.
- Future studies at SHEF might reduce uncertainties about effects of burning slash on water quality from fuel treatments near streams, but additional resources would be needed to address this question.
- Fuel treatment effects on sensitive spring and fen macroinvertebrates could also be studied at SHEF with additional resources.
- Regulators might use existing science products from SHEF to model long-term effects of wildland fire, fuel treatments, and climate change on Sierra Nevada water quality.

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Chapter 9: Ecoregion 6.2.14 Southern Rockies: Fraser Experimental Forest, Colorado

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Introduction

This chapter is a review and synthesis of research conducted at Fraser Experimental Forest (FEF) on stream chemical nutrients, contributing factors, and biological responses to them. It is intended to inform national and regional water quality regulatory agencies, such as the U.S. Environmental Protection Agency (USEPA) and the Colorado Department of Public Health and Environment (CDPHE), about existing results of relevant scientific studies that are available at FEF, and to identify future field and synthetic research of potential use to regulatory agencies that might be conducted at FEF.

Site Description

FEF is located on the west slope of the Rocky Mountain Front Range (lat. 39.90° N, long. 105.88° W), 7 km southwest of the town of Fraser, Colorado. The experimental forest occupies 9300 ha of federal lands in the Arapaho National Forest, with elevations ranging from 2680 to 3900 m (fig. 9.1). Climate is cool throughout the year. At the FEF headquarters (elevation 2765 m), the annual average temperature is 0.5 °C, and average monthly temperature is -10.0 °C in January and 12.7 °C in July. Mean annual precipitation is 737 mm with more than 65 percent usually occurring as snow.

The west side of FEF is rugged mountains with narrow, steep-sided valleys; whereas the south and east sides have gentle, relatively uniform slopes, and the north side is a broad valley dissected by St. Louis Creek (Alexander and Watkins 1977). Watersheds in the FEF were formerly glaciated, and their streams flow over moraines at varying elevations (Stottlemeyer 2001).

Sandy coarse soils are common across FEF and on its east side are primarily derived from a mixture of gneiss and schist metamorphic parent rock types. The soils are very permeable allowing high water infiltration into the soil profile and storing considerable water during snowmelt. At high elevations, especially on the west side, soils are derived from sandstones and are shallow with a high stone content. In areas along the main streams, soils are a mixture of alluvium, glacial till, glacial outwash, and recent valley fill (Alstatt and Miles 1983, Retzer 1962).

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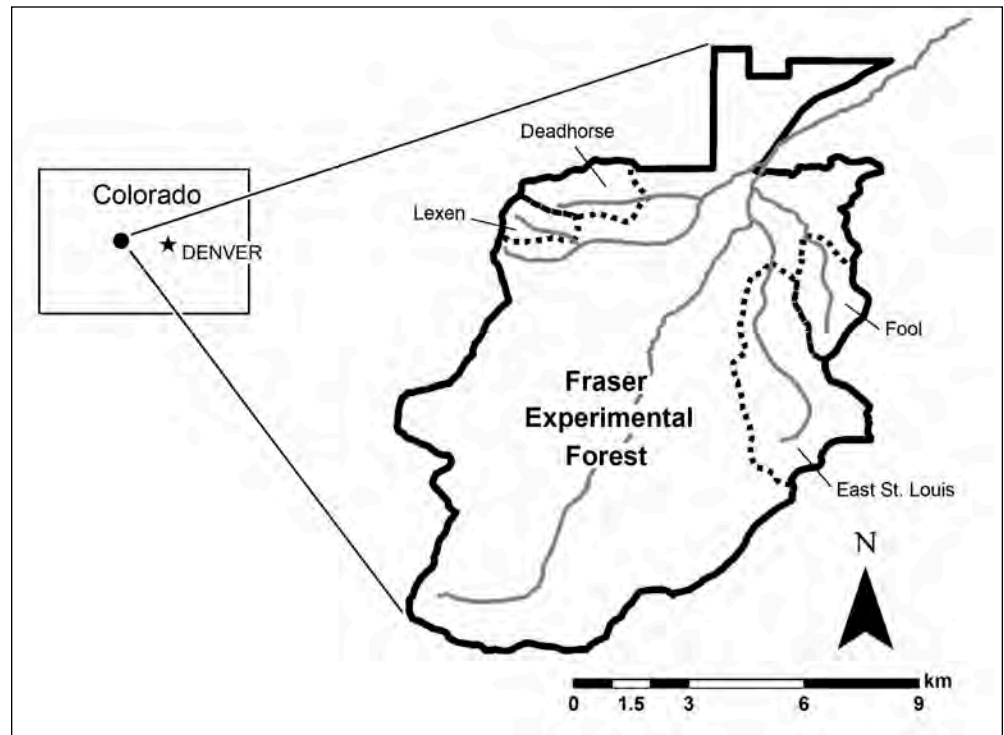


Figure 9.1—Fraser Experimental Forest near Fraser, Colorado, showing the locations of study watersheds.

FEF streams are generally steep with gravel beds and shallow pools, except in constrained reaches where bedrock ledges separate deeper pools. Large wood and boulders typically form roughness elements. The largest stream, St. Louis Creek, is perennial and fish bearing. Snowmelt in late spring and early summer typically dominates the annual hydrograph of St. Louis Creek and its tributaries. Immediately downstream of FEF study watersheds, St. Louis Creek's flow is partially diverted into water diversions for municipal drinking water supply for the city of Denver via a tunnel under the continental divide. Further downstream, St. Louis Creek joins the Fraser River which drains to the upper Colorado River near Granby, Colorado.

Vegetation zones consist of subalpine forests transitioning to alpine tundra at the higher elevations along the St. Louis Creek watershed divide. Below the tree line on north-facing aspects and on moist sites along streams, dominant tree species include Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), and aspen (*Populus tremuloides* Michx.). Lodgepole pine (*Pinus contorta* Douglas ex Loudon var. *latifolia* Engelm. ex S. Watson) is the dominant tree at lower elevations and on drier, south-facing slopes (Alexander et al. 1985).

Research History

FEF was established in 1937 by the U.S. Forest Service (USFS) and dedicated to research purposes. Continuous air temperature and precipitation data collection at FEF headquarters began in 1939. Initial investigations on FEF focused on timber and watershed research (Alexander 1987). In the 1940s and 1950s, paired watershed experiments were conducted to study effects of timber management on snowpack and water yield (Leaf 1975). Specifically, plot studies were designed to study the effect of differing levels of timber harvest on canopy, understory, litter interception, snowpack accumulation and melt, and soil water storage and depletion (Wilm and Dunford 1948). Continuous hydrologic and meteorological data have been maintained for eight watersheds since those initial experiments, giving FEF some of the longest continuous data records among experimental forests and ranges (EFRs) nationwide (Troendle and King 1985, 1987; Troendle and Reuss 1997). The chemistry of stream water, winter snowpack, soil solution, and precipitation have been monitored since the 1980s (Stottlemeyer 1987, 1997; Stottlemeyer et al. 1997). Although no formal National Atmospheric Deposition Program (NADP) monitoring has been located on the FEF, NADP protocols have been used at FEF to measure the chemistry of atmospheric deposition (NADP 2019a).

Many subsequent studies have investigated effects on stream chemistry and water cycles of various silvicultural practices at FEF, for example, Troendle and Nilles (1987), Reuss et al. (1997), Stottlemeyer and Troendle (1999), and Stottlemeyer (2001). Processes that have been examined at FEF include tree canopy interception of atmospheric chemical inputs, effects of clearcutting on nutrient flux, and soil processes occurring under snowpack, such as seasonal carbon dioxide flux (Hubbard et al. 2005, Reuss et al. 1997, Stottlemeyer and Troendle 1997). Recent research has investigated the effects of large-scale tree mortality caused by the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) on stream chemistry and water balance, and effects on streams from salvage logging of beetle-killed trees (Hubbard et al. 2014; Rhoades et al. 2013, 2017).

Research on snowpack accumulation and snowmelt dynamics and modeling, including potential responses to alternate climate change scenarios, has also been a recent emphasis (Lisle et al. 2010, Rhoades et al. 2010, Rutter et al. 2009). Snow monitoring at FEF has included an active U.S. Department of Agriculture Natural Resource Conservation Service snow telemetry (SNOTEL) site in operation in the Fool Creek watershed, established October 2011. Another ongoing line of water research at FEF seeks to understand water use, storage, and evapotranspiration dynamics of dominant tree species, such as lodgepole pine, Engelmann spruce, and subalpine fir, to improve understanding of how changes in subalpine tree species composition might affect water yield locally and at the watershed scale (Elder et al. 2006, Kaufmann 1985).

Availability of publications and data—

Although no comprehensive, up-to-date bibliography of FEF scientific publications and research is currently available, bibliographical lists and researcher contact information may be obtained through several websites. The USFS Rocky Mountain Research Station (RMRS) provides general FEF information and contacts, and a search engine for USFS-sponsored research. USFS website links include an overview and personnel contacts for FEF research (USDA FS 2017a). Streamflow, temperature, carbon, and precipitation data can be found at USDA FS (2017b), and publications can be found at the USFS publication search engine (USDA FS 2017c). The RMRS Air, Water and Aquatic Environments Program provides information about various research, data, publications, and biogeochemistry laboratory services (USDA FS 2017d).

The U.S. Department of the Interior Geological Survey (USGS), Fort Collins Science Center provides information about research sponsored by the center, some of which is associated with FEF (USDI GS 2017a). The USGS National Water Information System provides FEF St. Louis Creek water information site data (USDI GS 2017b).

The USEPA STORET water quality data storage and retrieval site contains data collected on St. Louis Creek and adjacent watersheds (US EPA 2017).

Warner College of Natural Resources, Colorado State University in Fort Collins describes its current and past faculty and graduate research, some of which has been done at FEF (CSU 2017).

Grand County Water Information Network provides water quality data archives, which include data collected on St. Louis Creek (GCWIN 2017a, 2017b).

Long-term FEF daily streamflow and meteorological data, formatted for comparison with other EFRs, can be downloaded from the Long Term Ecological Research [LTER] Network (LTER 2017).

Natural Resource Conservation Service SNOTEL (Fools Creek Basin) provides telemetry and snow course data and related products (USDA NRCS 2017).

National Aeronautics and Space Administration National Snow and Ice Data Center provides a link to the Cold Land Processes Field Experiment and related data for FEF (NASA 2017).

Biological Responses to Stream Nutrients N and P

Issues of Concern

As are many mountain watersheds along the Colorado Front Range, FEF is a source of high-quality water for Denver's municipal drinking water system. St. Louis Creek, the main drainage on the FEF, is typical of headwater streams that are the source of 85 percent of the annual yield of water from the Colorado Rockies (Alexander et al. 1985). Excess stream water nitrogen (N) and phosphorus (P) can contribute to poor water quality in drinking water reservoirs and degradation of habitats for desirable fish (Fenn et al. 1998), and can detract from the quality of recreational activities such as swimming, whitewater rafting, and sport fishing, which are economically important in the region.

Nutrients originating from urban, agricultural, and industrial emission sources can be transported through atmospheric pathways and deposited in high-altitude watersheds, potentially contributing to water quality degradation. Periodic disturbances from wildland fires and tree mortality from insect attack can also increase stream water nutrient concentrations. Although forest management, such as stand thinning and salvage cutting, may temporarily elevate stream nutrients, these practices are sometimes used to reduce the risks posed to streams and other resources by severe fires and insect outbreaks.

Findings From Studies

Since 1982, streams at FEF have been regularly monitored for ammonium (NH_4^+) and nitrate (NO_3^-) (Stottlemeyer 1987, 2001). Stottlemeyer and Troendle (1997) analyzed FEF stream water, snowpack, and soil ion concentrations for a variety of chemicals, but did not report results for phosphate (PO_4^{3-}), presumably because concentrations were lower than they could reliably detect.

At FEF, nutrient concentrations in snowpack and stream water increase with elevation, with the highest concentrations of NH_4^+ and NO_3^- in the alpine zone (Stottlemeyer 1987, Stottlemeyer et al. 1997). For example, water draining the high-elevation, alpine portion of the Lexen Creek reference watershed contained NO_3^- concentrations that were 2 to 10 times higher than stream water in the subalpine portion, at lower elevation in the watershed. As alpine streams transitioned to the subalpine forest, stream water NO_3^- concentrations typically decreased (Stottlemeyer 1997). This pattern was explained by postulating that, compared to subalpine forests, alpine areas had more direct routing of snowmelt water to streams via exposed rock and alpine tundra that effectively bypassed storage in groundwater and vegetative nutrient uptake.

In contrast to the alpine areas, most snowmelt in subalpine watersheds is routed through subsurface flow (Stottlemeyer 1997, 2001). Soil processes such as ion exchange, biological uptake, overwinter nitrification, and mineralization are probably major factors modifying the chemistry of meltwater before it reaches streams. No correlation was found between soil water chemistry and stream water chemistry, which probably reflects a high variation in distance travelled and degree of chemical processing of soil water as it moves to streams. Alpine stream water ion concentrations change little during snowmelt, suggesting that meltwater passes quickly through porous soils and is well mixed before entering streams. By contrast, in lower elevation subalpine streams, ion concentrations are diluted during snowmelt (Stottlemeyer 2001). In subalpine soils, minor changes in the depth of lateral subsurface flow significantly affects the export of ions. Snowmelt apparently changes the depth at which water moves through subalpine soils to streams.

Nutrient effects on aquatic food webs and related factors—

Biological effects of nutrient enrichment and light regimes along a 400-m stretch of West St. Louis Creek were studied by Wellnitz et al. (1996). They examined four light treatments, including artificial shading of a stream reach with no riparian canopy shade, closed canopy, artificial illumination in the closed-canopy reach, and open canopy. To investigate nutrient effects, clay flower pots, filled with cobbles, were placed in streams and received nutrient additions that diffused from agar gels containing 0.5 molar concentrations of nitrate as NaNO_3 and phosphorus as KH_2PO_4 either separately or in combination. They found that periphyton and algae abundance responded similarly under open- and closed-canopy treatments. Primary production was reduced in artificial shade, but under artificial lighting it was significantly increased by a factor of two to four. In addition, they found the combined N+P mixture had the greatest effect on periphyton and algal biomass and chlorophyll *a* production under all lighting treatments, suggesting that both nutrients are probably important for eutrophication of mountain streams. Overall, the artificial lighting had a greater effect on the algal community than nutrient enrichment. The artificial light treatment demonstrated that the potential for algal biomass production in West St. Louis Creek was probably not fully achieved owing to photoinhibition. The authors cautioned against extrapolating from their results to conclusions about how the West St. Louis Creek ecosystem would respond to N and P enrichment because their experiment had used nutrient diffusion and artificial substrates.

Surveys at FEF of stream organisms under ambient nutrient conditions have mainly consisted of fish surveys. Fish species present and their population trends have been periodically monitored by the Arapaho National Forest at an established index reach on St. Louis Creek within FEF. Fish species occurring in St. Louis

Creek and some of its tributaries have historically included native cutthroat trout (*Oncorhynchus clarkii* Richardson), mottled sculpin (*Cottus bairdii* Girard), non-native brook trout (*Salvelinus fontinalis* Mitchill), and rainbow trout (*O. mykiss* Walbaum). The most recent population estimate was approximately 330 fish per kilometer in 2005, primarily brook trout, with no other trout species found (USDA FS 2008). Indigenous cutthroat trout, previously found in FEF streams, may have been extirpated (Elder et al. 2006, Young et al. 1996), although this finding has not been confirmed by extensive field sampling or eDNA analyses. Stream surveys of algae and macroinvertebrates, trophic groups that are often used by water quality regulatory agencies to assess water quality, have not been conducted at FEF.

Other Factors Relevant to Stream Nutrients N and P

Hydrological influences—

In contrast to limited biological monitoring, numerous environmental factors that may affect stream nutrients and biological response have been extensively studied or monitored in FEF. Studies have found that East St. Louis Creek has stable geomorphology under a variety of flow conditions, and woody debris was an important sediment storage element (Adenlof and Wohl 1994, Trayler and Wohl 2000). Although the loading of large wood in East St. Louis Creek was high, the proportion of wood in jams was low because the relatively small contributing area produced flows insufficient to mobilize large wood (Wohl and Jaeger 2009). Earlier research showed that cross-channel logs in Fool and Deadhorse Creeks formed steps by holding back coarse sediment and decreasing flow velocities (Heede 1972), a process that affects stream nutrient cycling. More recent research on streamflow characteristics, channel hydraulics, and reach-level spatial modeling used state-of-the-art technologies, including acoustic Doppler and terrestrial LiDAR on streams at FEF (David et al. 2013, Yochum et al. 2014). These more sophisticated methods not only validated previous work but provided further insights into flow dynamics by quantifying the spectrum of geomorphic change in these high-gradient channel types.

Stream temperature—

Long-term stream temperature monitoring by the Arapaho National Forest is located on St. Louis Creek downstream of the Denver Water Board diversion structure within FEF (fig. 9.1). The timing of snowpack runoff and cool summer temperatures make it rare for St. Louis Creek to exceed water quality standards for temperature. In contrast, the Fraser River, downstream of FEF, is listed as impaired for temperature, and summer maximum water temperatures frequently exceed 16 °C (USEPA 2015).

Signs of changing stream conditions owing to climate warming have been observed at FEF. Jones et al. (2012) reported that spring runoff in recent years at FEF occurs significantly earlier in the season than it did in the mid-20th century, expanding the period of thaw, presumably because the climate has warmed. They also found that minimum daily air temperatures have also increased significantly by several degrees Celsius since 1980. It is not currently known whether increasing ambient air temperature and a longer period of thaw have influenced stream biological communities or their responses to stream nutrients.

Reference Watersheds

Lexen Creek (140 ha) and East St. Louis Creek (940 ha) watersheds on the FEF have been managed for minimal human disturbance since the 1940s and have served as reference watersheds for many studies. These watersheds represent conditions that are probably similar to other relatively undisturbed watersheds along the Front Range that are within a similar elevation range. Streamflow has been continuously monitored from these reference watersheds since the 1940s, and stream nutrients, including NO_3^- and NH_4^+ , have been monitored regularly since 1982.

An analysis of trends found significantly increasing stream water NO_3^- concentrations in both FEF reference watersheds from 1997 to 2007 (Argerich et al. 2013). For the same period, streamflow significantly decreased, and NH_4^+ decreased slightly. These findings corroborate those of Baron et al. (2000), who reported increasing NO_3^- in high-altitude streams on the east side of the Colorado Front Range, suggesting this trend in stream NO_3^- may be common in high-altitude streams in this region. Wet deposition of NH_4^+ and NO_3^- measured at FEF did not change significantly from 1987 to 2007 (Argerich et al. 2013).

Onsite meteorology and upland vegetation have also been monitored on these reference watersheds. Upland vegetation has been subject to tree mortality from mountain pine beetles. To maintain minimal human disturbance, no actions have been taken on these reference watersheds to either prevent mortality or remove dead or dying trees. The levels of naturally caused vegetation disturbance on these reference watersheds are probably typical for minimally disturbed watersheds in this region and this altitude range. To date, no surveys or studies have been conducted of the stream biological communities in these undisturbed reference streams. Fish surveys conducted by Arapaho National Forest on the main stem of St. Louis Creek did not extend upstream into these reference basins.

Cross-Site and Regional Studies

The FEF has often been included in regional and national cross-site studies. Studies comparing FEF streams with other, similar mountain streams in Colorado and Wyoming found that bedload transport occurred over a narrow range of discharge, typically between 60 and 100 percent of bankfull flow, and that channels were fairly stable in undisturbed watersheds (Ryan et al. 2005, Troendle and Olsen 1994). Stottlemeyer (1997) used data from the Lexen Creek reference watershed in FEF, plus two sites in Michigan, and one in Denali National Park, Alaska, to compare stream water chemistry across a broad geographic range with the objective of finding correlations to atmospheric inputs. Overall, only weak or insignificant correlations were found between precipitation and stream water ionic concentrations including NO_3^- . Atmospheric deposition measurements generated from FEF studies have been compared with measurements from regional NADP sites (Stottlemeyer 1987, 2001; Stottlemeyer and Troendle 1992; Stottlemeyer et al. 1997).

In a cross-site comparison of seven experimental forests from across the United States, Argerich et al. (2013) found that stream water NO_3^- concentrations in FEF reference watersheds, East St. Louis and Lexen Creek, were comparable with the other western site in the study, H.J. Andrews Experimental Forest in Oregon (see chapter 5), but low compared to streams at Hubbard Brook (see chapter 3) and Fernow Experimental Forests (see chapter 13) in the Eastern United States.

In a cross-site analysis of long-term hydrologic response to precipitation and climate among 35 EFR and LTER sites nationwide that included FEF, Jones et al. (2012) found that the higher minimum daily temperatures and a lengthening period of thaw in response to climate warming at FEF were similar to other subalpine sites in the Rocky Mountains.

Dose-Response Studies

The only published dose-response study at FEF has been the work by Wellnitz et al. (1996), which assessed potential effects on stream primary productivity of various N and P enrichments and light regimes using artificial substrates in St. Louis Creek. This study is described in more detail above under the heading “Nutrient effects on aquatic food webs and related factors.”

Responses to Forest Management and Natural Disturbances

Research at FEF that investigated effects of silvicultural practices on hydrology has provided a scientific basis for guiding USFS land management practices. Research findings of Troendle and Olsen (1994), for example, were used in the development of forest plan standards and guidelines and best management practices (BMPs)

for timber harvest and road design on National Forest System lands. BMPs were intended to mitigate potential effects of timber harvest such as increased runoff and flood flows, which, in turn, may affect channel integrity, sediment loading, riparian vegetation, and water quality.

Timber harvest in subalpine forests at FEF has been found to strongly affect streamflow regimes, potentially affecting nutrient dynamics, sediment flux, and aquatic habitats. A review of historical streamflow records before and for 28 years after a timber harvest in 1956 in the Fool Creek watershed found that in the post-harvest period, seasonal flow increased 40 percent, and spring peak flow increased 20 percent (Troendle and King 1985). Streamflow seasonal variability can have strong effects on bedload movement and nutrient cycling in headwater streams with high-gradient channels and a large stock of woody debris roughness elements. For example, Troendle and King (1985) noted that the duration of bankfull discharge, the most effective discharge for sediment transport, doubled following timber harvest on Fool Creek. Increased sediment transport on the nearby North Fork of Deadhorse Creek was attributed solely to increased discharge and channel scour following partial clearcutting (Troendle and King 1987).

Clearcut harvesting experiments at FEF found that snowpack runoff and stream water quality were affected by increasing snowpack peak water equivalent by an average of 36 percent over reference uncut forests, and by increasing peak stream discharge (Troendle and King 1985, 1987; Troendle and Reuss 1997). In addition, clearcut logging increased NO_3^- concentrations in the snowpack compared to forested areas, whereas NH_4^+ concentrations were lower in snowpack in clearcuts (Stottlemyer and Troendle 2001). A companion study found that, compared to uncut reference watersheds, which typically served as sinks for atmospherically deposited N, clearcut harvesting elevated NO_3^- concentrations in drainage water and caused significant stream export of N at the onsite and hillslope scales (Reuss et al. 1997). Taken together, these findings suggested that clearcutting increased N export by both increasing NO_3^- deposited to snowpack and decreasing biological assimilation and retention of NO_3^- released during snowmelt at FEF.

Salvage logging of beetle-killed trees may alter future forest diversity and fuel types by promoting conditions more favorable to lodgepole pine and aspen regeneration than to subalpine fir (Pelz et al. 2015). This shift in tree species may have implications on future water yield, water chemistry, and fire hazards (Collins et al. 2011, 2012).

Wildland fire, the primary source of natural disturbance to forests in this region, can alter stream nutrient levels. For example, the Hayman Fire of 2002,

Colorado's largest historical wildfire, increased postfire stream water NO_3^- concentrations (Rhoades et al. 2006). Temporary postfire nutrient enrichment, coupled with increases in solar radiation and temperature from postfire loss of vegetative canopy cover, can produce a short-term increase in aquatic primary productivity.

Wildland fires in the subalpine spruce and lodgepole pine forests at FEF were historically infrequent, but occasionally severe, and stand replacing. Using average tree cohort age as a surrogate, Huckaby and Moir (1995) estimated that historical wildfire return intervals ranged from 64 to 389 years. The establishment of fire suppression measures at FEF effectively eliminated wildland fire as a major disturbance mechanism since the early 1900s. The lack of wildland fire has resulted in overstocked forest conditions, which, along with periodic droughts, may increase the risk of severe, stand-replacing fires in the future.

These ecological conditions have also stressed trees, making them vulnerable to mortality from the mountain pine beetle, which is common along the Front Range. Beetle infestation levels at FEF peaked around 2007. Research has assessed pre- vs. postinfestation tree mortality effects on water chemistry and water yield. For example, stream water total dissolved inorganic N was higher in old-growth reference watersheds with extensive beetle kill compared to the pre-beetle outbreak period, yet NO_3^- concentrations were unaffected in mixed-age forest stands (Rhoades et al. 2017). Nutrient demand by understory and live overstory trees in upland and riparian areas may balance the elevated soil nutrients measured beneath beetle-killed trees thus neutralizing effects on export to streams. Compared to wildland fires, increases in stream water NO_3^- concentrations after beetle-caused tree mortality were moderate (Hubbard et al. 2014; Rhoades et al. 2008, 2013). The modest response to beetle kill was attributed to a combination of lower atmospheric N deposition locally in the beetle-kill area, gradual tree mortality spread over multiple years, and high compensatory capacity of residual vegetation and soils. An FEF watershed with substantial beetle-induced mortality showed a response in stream NO_3^- flux that was smaller than the response that followed a partial harvest (30 percent of area harvested) in a nearby watershed (Rhoades et al. 2013).

Reliability and Limitations of Findings

FEF data and research findings are of high quality and are probably most applicable to high-elevation forests near the subalpine-alpine transition of the Colorado Front Range. Outside of these conditions, or where additional accuracy is required, validation studies or monitoring might be advisable at other locations to test how well FEF represents local conditions.

Research Needs

An important science gap at FEF and the highest priority research need related to nutrient pollution is characterization of biological communities, including algae, macroinvertebrates and fish, in undisturbed reference streams on the FEF, and better understanding of how these communities respond to increases in stream nutrient concentrations. Filling this science gap is important because surveys of stream community composition at FEF might be used to confirm or extend what is known about reference conditions in other minimally disturbed Colorado montane streams (e.g., Lewis and McCutchan 2010). FEF studies might also be used to determine at what threshold levels, and after how much time, reference stream communities change in response to nutrient enrichment. Such studies might also investigate whether other factors, such as temperature, might be controlling nutrient response in these mountain streams. Filling this gap would require conducting surveys of stream biological communities in FEF reference streams. These surveys would be most valuable if substrate type, stream width, streamflow, canopy cover, total and dissolved N and P, pH, dissolved oxygen, alkalinity, and water temperature were included in the analysis. Community responses to nutrient enrichment might be inferred by comparing reference communities in FEF streams with biotic communities in other, more enriched, Colorado montane streams. Experimental stream enrichments might also be useful to determine response thresholds, especially if they included effects of adding both N and P, in various combinations and concentrations. Studies should be continued long enough (>5 years) to detect delayed biological and food web responses similar to those observed by Davis et al. (2010) at Coweeta Hydrologic Laboratory (see chapter 14). Utilizing multivariate data analytical tools, such as those of Baker and King (2010), might make community effects of nutrient enrichment more detectable, especially in contrast to aggregating community data into univariate responses, such as diversity and richness, as were evaluated by Lewis and McCutchan (2010).

Other research questions of interest that might be filled at FEF include (a) what are the effects of observed increasing ambient air temperature at FEF on stream temperature and biological response to stream nutrients, and (b) to what degree is stream water NO_3^- concentration driven by atmospheric deposition of N?

Potential Utility to Water Quality Regulatory Agencies

The FEF and other experimental forests and ranges provide extremely valuable long-term data that might be used to define reference or near-reference conditions. A great challenge in deriving numeric nutrient criteria for any waterbody is identifying

lowest concentrations of N and P that produce undesirable impairment from attainment of designated uses, such as fishing, swimming, and protection of aquatic life. This threshold is to some degree subjective, and how far it may deviate, if at all, from a reference or near-reference condition is debatable. Ultimately, the criteria are based upon a judgment of what is needed to protect designated uses. To minimize risk to aquatic biota, some states are developing nutrient criteria to maintain the natural condition in their highest quality waters. Enrichment above naturally occurring levels departs from conditions to which biota have evolved over a very long time, and when species and unique assemblages are lost, restoration can be extremely difficult, expensive, and improbable in most cases. Maintaining the natural condition would require understanding the physical, chemical, and biological conditions that exist in reference streams. The FEF and other experimental forests and ranges provide an extensive record of documented natural stream conditions in carefully maintained reference watersheds.

Another challenge is how to include in the development of water quality criteria, observations that background conditions in reference watersheds have not been static, but have undergone changes from regional or global-scale anthropogenic or natural influences. Research results and long-term monitoring datasets at FEF may be useful in addressing this issue because they provide scientific evidence that, even in high-altitude reference watersheds that have been scrupulously protected from onsite human disturbance, stream water NO_3^- concentrations have increased in recent decades (Argerich et al. 2013). Therefore, the importance of FEF as a natural laboratory to examine the effects from natural and anthropogenic disturbances cannot be overstated. Continued monitoring will allow us to assess current conditions, provide early warning if conditions decline, and monitor effects of various environmental disturbances.

Finally, in addition to the value of FEF streams for documenting reference conditions, existing long-term datasets and research results from other streams on the FEF may be used to evaluate impacts from forest management practices. Research results from forest management experiments at FEF may be of practical use for developing BMPs that provide guidance for protecting water quality during forest management activities in other high-altitude basins. Outside of FEF, carefully controlled studies of the effects of active forest management on streams are rare along the Front Range, in part because management experiments are difficult to implement or are not permitted in some other study watersheds in the region, for example, those managed as wilderness or in national parks.

Key points:

- FEF has publicly available, high-quality, and long-term hydrology, temperature, meteorological, and stream water N data.
- Forestry-related effects on stream water flows and N chemistry have been well studied at FEF, resulting in many reports and published articles.
- Apart from fish surveys along St. Louis Creek, and a study of stream algal response to nutrient enrichment on artificial substrates by Wellnitz et al. (1996), there has been relatively little research on aquatic biology at FEF, providing many opportunities for future study.
- The highest priority research need, for the purpose of addressing nutrient pollution, is to characterize existing biological communities, including algae, macroinvertebrates, and fish in relatively undisturbed reference streams on the FEF, and to determine at what threshold levels, and after how much time, reference stream communities change in response to nutrient enrichment.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Currently, there are also water quality concerns related to other nutrients, such as sodium (Na) and selenium (Se), in the region; however, levels in atmospheric deposition at FEF for nutrients other than N, P, and heavy metals have historically been low. Deposition of some of these elements, however, could increase in high-altitude ecosystems along the Front Range, including FEF, if air emissions from fossil fuel production and combustion increase in regions upwind. For example, atmospheric deposition of sulfur (S), if high enough, could contribute to the acidification of stream systems.

Atmospheric deposition of S might also contribute to increased accumulation of mercury (Hg), a neurotoxin, in apex predators of aquatic food chains, which includes fish commonly consumed by people. Research in wetlands at Marcell Experimental Forest (see chapter 2) has found that, under some circumstances, deposition of the nutrient sulfur, as sulfate (SO_4^{2-}), can increase uptake of Hg in food chains (Jeremiason et al. 2006). Thus, although Hg is not itself a nutrient, the risk this toxin poses to humans is amplified by stream food chains and, under some circumstances, might be further heightened by ambient levels of the nutrient S.

Ground-disturbing activities, such as mining, have not occurred within FEF, but in some parts of the Front Range, drainage from mines and mine spoil has

degraded water quality with pollutants, including high acidity, SO_4^{2-} , heavy metals, and sediment loads. These water pollutants can negatively affect fish and other aquatic biota, and may also affect use of streams for water-contact recreation and drinking water supply. FEF has the potential to provide important information on background stream conditions in high altitude Front Range basins in the absence of mining disturbance.

Findings From Studies

Metals and bacteria—

Since the mid 1980s, stream water, snowpack, soil solution, and atmospheric deposition at FEF have been monitored for calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), chloride (Cl^-), and SO_4^{2-} , along with pH, electrical conductivity, and acid neutralizing capacity (ANC).

In addition, three water quality monitoring sites, station numbers 12165, 12165B, and 12165C, have been maintained within FEF by the CDPHE on St. Louis Creek (CDPHE WQCC 2010). At these sites, stream water has been monitored for major metallic cations, including copper (Cu), iron (Fe), manganese (Mn), Se, and zinc, plus the bacteria *Escherichia coli* and fecal coliform. As expected, these data indicate that levels of these metals in streams within FEF, which has not been mined, are low compared to streams draining some mining areas. Other than a single fecal coliform detection in 1997, bacteriological monitoring has found no contamination.

Other Factors Relevant to Stream Nutrients N and P

Other factors that might affect biological response to stream nutrients other than N and P are the same as those related to N and P that are described above under “Biological Responses to Stream Nutrients N and P.”

Reference Watersheds

The nutrients Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , and SO_4^{2-} have been monitored in streams on FEF reference watersheds since the early 1980s. Variations in stream chemistry observed among FEF watersheds, including the reference watersheds, were correlated with basin lithology. For example, the mean pH of St. Louis Creek and its tributaries is 7.8 standard unit (SU) and ranges from 7.4 to 8.1 SU, with higher values in streams on sedimentary bedrock. Also, pH, Ca^{2+} , Mg^{2+} , ANC, and electrical conductivity of stream water were higher in basins with mixed geology (Nelson et al. 2011). Concentrations of nutrients other than N and P in FEF reference streams did not show any significant trends over time.

Cross-Site and Regional Studies

Atmospheric deposition of SO_4^{2-} at FEF, measured by Stottlemeyer (1987, 1997), was similar to other high-elevation NADP stations in the Rocky Mountains.

Mercury has not been measured in deposition, stream water, or food chains at FEF, and regional analyses are contradictory about what levels might be expected. The Western Airborne Contaminants Assessment Project (2002–2007) measured deposition of heavy metals, such as Hg, and of semivolatile organic compounds, including pesticides, across 20 western national parks and monuments (Hageman et al. 2010, Landers et al. 2018). The nearest site studied was Rocky Mountain National Park, about 65 km north of FEF. Sites on the eastern side of Rocky Mountain National Park had elevated Hg levels in snowpack, along with some of the highest levels of semi-volatile organic compounds in the survey. In contrast, NADP maps of regional Hg deposition predict relatively low Hg deposition ($<9 \mu\text{g}/\text{m}^2$) in the vicinity of FEF (NADP 2019b). These maps are based on NADP Hg monitoring sites, the closest of which is Fort Collins, 100 km northeast of FEF. Whether current environmental levels of Hg at FEF are high, as Western Airborne Contaminants Assessment Project results suggest, or low, as NADP deposition maps seem to indicate, may remain unresolved until measurements of Hg in deposition, stream water, and food chains are made at FEF.

Responses to Management and Natural Disturbances

Clearcut timber harvest at FEF increased Ca^{2+} , Mg^{2+} , Na^+ and K^+ ions in stream water (Reuss et al. 1997), but in snowpack, clearcut logging produced concentrations of K^+ and H^+ that were lower than in forested areas (Stottlemeyer and Troendle 2001).

The primary source of natural disturbance to forests in this region, wildland fire, can alter levels of nutrients other than N and P in streams. For example, the Hayman Fire of 2002, which occurred about 100 km southeast of FEF, increased postfire stream water Ca^{2+} , K^+ , and ANC and decreased stream SO_4^{2-} and Cl^- (Rhoades et al. 2006). Studies of beetle-caused mortality of trees at FEF (Hubbard et al. 2014, Rhoades et al. 2008) did not examine stream nutrients other than N and P.

Research Needs

From a water quality perspective, there are no research needs of high priority related to nutrients other than N and P that need to be filled at FEF at this time. Most current management efforts are focused on N and P because they are considered to be the principal drivers of eutrophication.

Potential Utility to Water Quality Regulatory Agencies

Existing FEF datasets and research findings on atmospheric deposition of pollutants might be helpful in determining whether measures to control such pollutants are effective for protecting water quality in high-elevation streams along the Front Range. In the future, continued environmental monitoring at FEF might serve as an early warning for changes in atmospheric deposition and whether such changes have the potential to affect water quality.

Key points:

- Reference watersheds with minimal anthropogenic disturbance provide important opportunities to study water quality changes that may result from atmospheric deposition of pollutants from offsite sources, in addition to changes from other disturbances such as insect outbreaks and warming climate.
- Continued monitoring at FEF might be useful by providing early warning of changes in atmospheric deposition that could potentially affect water quality in mountain streams.
- For purposes of addressing nutrient pollution, there are no research needs of high priority related to nutrients other than N and P at this time.
- The FEF has publicly available, high-quality and long-term hydrology, temperature, meteorological, and stream chemical data.
- The FEF is an important reference site in the region and has also been used in nationwide comparison studies.
- Low levels of anthropogenic disturbance maintained at FEF provide useful opportunities to monitor effects of contaminant deposition from atmospheric pathways and provide early warning of changes that could affect aquatic ecosystems.
- Controlled forestry management experiments on the FEF are useful for developing science-based BMPs designed to protect water quality and aquatic ecosystems.
- The highest priority research need at FEF, for the purpose of addressing nutrient pollution, is to characterize existing biological communities, including algae, macroinvertebrates, and fish in relatively undisturbed reference streams, and to determine at what threshold levels, and after how much time, reference stream communities change in response to enrichment with N and P.

Overview and Synthesis

The study watersheds at FEF are typical of the high-altitude, snow-dominated basins that produce ~85 percent of the water yield from the Colorado Rocky Mountains Front Range. These alpine basins are especially important because they provide not only a primary source of high-quality drinking water in this region but other beneficial uses such as habitat for aquatic life, fishing, boating, and swimming. They are also used for agricultural purposes and by local businesses. Although these alpine ecosystems are well adapted to survive the harsh mountain climate, and are relatively isolated from many human activities, they may be susceptible to a variety of influences that could alter water quality in mountain streams. Decades of research and monitoring at FEF have measured water quantity and water quality impacts from common forest management practices and natural disturbances in these high-altitude basins. Controlled investigations of the effects of forest management practices on FEF streams may help to better inform BMP strategies to protect stream systems. Studies at FEF may also be useful for investigating how regional and global influences such as deposition of air pollution and climate warming might affect water quality and aquatic communities in reference watersheds. Evidence that NO_3^- concentrations in FEF reference streams have significantly changed over recent decades raises questions about how to incorporate “baseline” reference conditions that are not static into the development of water quality criteria. Finally, the highest priority research need at FEF to address nutrient pollution is to characterize existing biological communities including algae, macroinvertebrates, and fish in relatively undisturbed reference streams, and to determine at what threshold levels, and after how much time, reference stream communities change in response to enrichment with N and P.

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Chapter 10: Ecoregion 6.2.14 Southern Rockies: Glacier Lakes Ecosystem Experiments Site, Wyoming

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Introduction

This chapter is a review and synthesis of research conducted at Glacier Lakes Ecosystem Experiments Site (GLEES) 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 and Wyoming Department of Environmental Quality (WDEQ), about existing results of relevant scientific studies that are available at GLEES, and to identify future field and synthetic research of potential use to regulatory agencies that might be conducted at GLEES.

Site Description

GLEES is located in the Snowy Range of the Medicine Bow Mountains, south-east Wyoming (Musselman 1994). The site (lat. 41° 22' 30" N, long. 106° 15' 30" W) is 1297 ha within the Medicine Bow National Forest, 15 km northwest of Centennial, Wyoming. GLEES is at the alpine and subalpine ecotone, with an elevation range of 3120 to 3494 m. Vegetation consists of subalpine forest, dominated by mature Engelmann spruce (*Picea engelmannii*, Parry ex Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) interspersed with wetlands and meadows (Musselman 1994, Regan et al. 1998). The site has three glacial cirque lakes within areas of glacial till and first-order streams that flow from late spring through fall, but are frozen in winter (fig. 10.1). The site was glaciated <15,000 years BP (Mensing et al. 2011) and has young, shallow, rocky soils and numerous areas of exposed bedrock and scree fields. Bedrock is primarily quartzite with intrusions of more weatherable mafic dikes. The growing season is short and relatively harsh, with snow on the ground from early November until mid-June, and lakes that are ice free only from mid-June to mid-October. Precipitation at GLEES averages 129 cm per year, with 85 percent falling as snow (Dwire, n.d.). Average daily temperature is about -10 °C in winter (January and February) and rarely exceeds 16 °C in mid-summer (fig. 10.2). Freezing temperatures can occur any month of the year.

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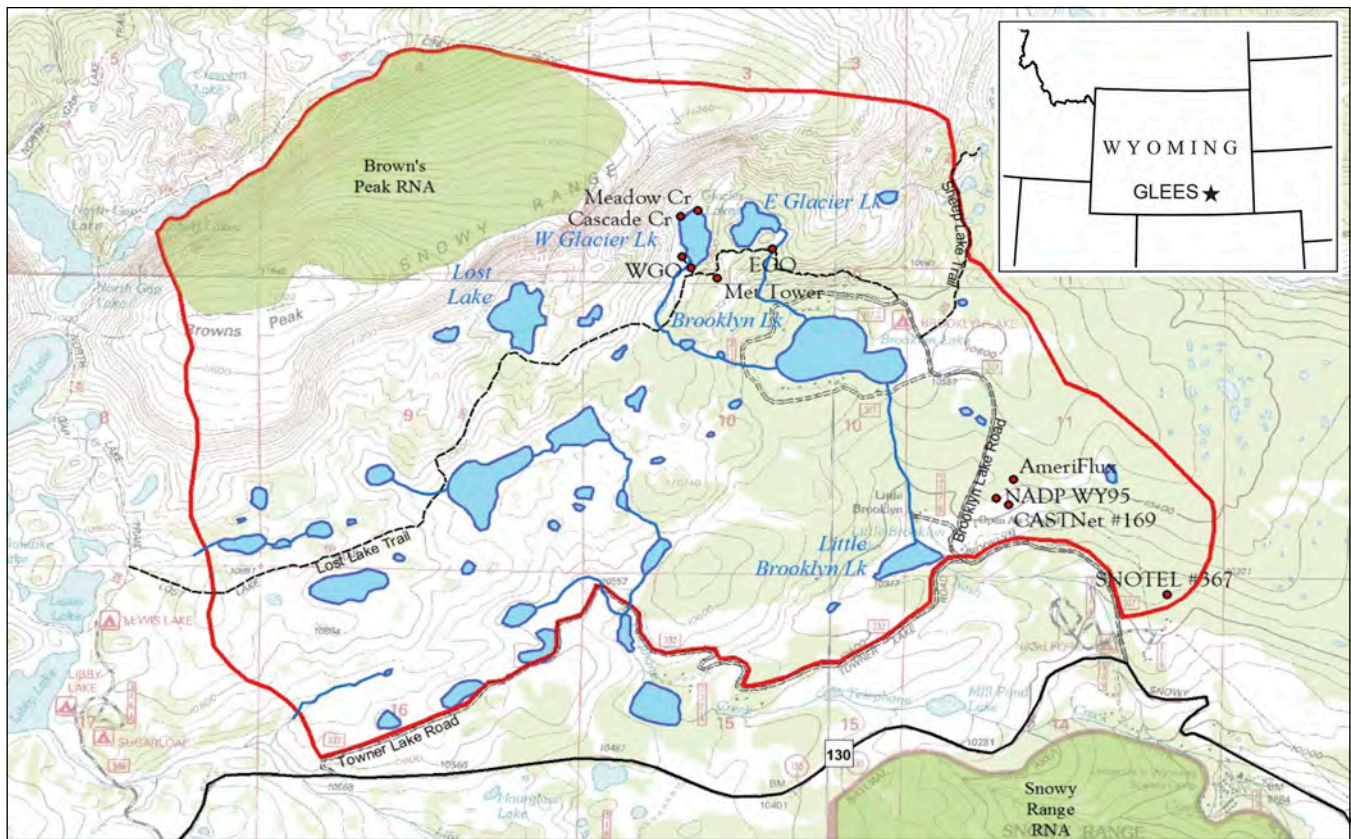


Figure 10.1—The Glacier Lakes Ecosystem Experiments Site (GLEES) showing access roads and trails, primary surface waters, and monitoring facilities. Experimental facilities include the meteorological tower and national networks: National Atmospheric Deposition Program (NADP), Clean Air Status and Trends Network (CASTNet), Snow Telometry (SNOTEL), and AmeriFlux. Parshall flumes are located at Meadow Creek, Cascade Creek, West Glacier Outlet (WGO), and East Glacier Outlet (EGO). RNA = research natural area.

Research History

GLEES was established in 1987 to examine the response of subalpine ecosystems managed as wilderness to long-term atmospheric deposition and climate changes. Research instrumentation and infrastructure can be installed at GLEES because it is not within an officially designated U.S. Forest Service wilderness area where such equipment would be prohibited. Baseline vegetation plots were established in the late 1980s and early 1990s (Regan et al. 1998), when meteorology and hydrological monitoring at East and West Glacier Lakes, and associated streams were also initiated (fig. 10.1) (Musselman 1994). The site is not used for vegetation manipulation studies, such as silvicultural treatments, that might alter ecosystem structure and processes. The primary focus of GLEES research is to examine changes to surface waters and ecosystems over time. The site is now also used to study ecosystem response to bark beetle mortality of mature forest overstory trees at the treeline ecotone that were killed in a recent bark beetle epidemic. The spruce beetle (*Dendroctonus rufipennis*) is attacking Englemann spruce, and the western balsam bark beetle (*Dryocoetes confusus*) is attacking subalpine fir.

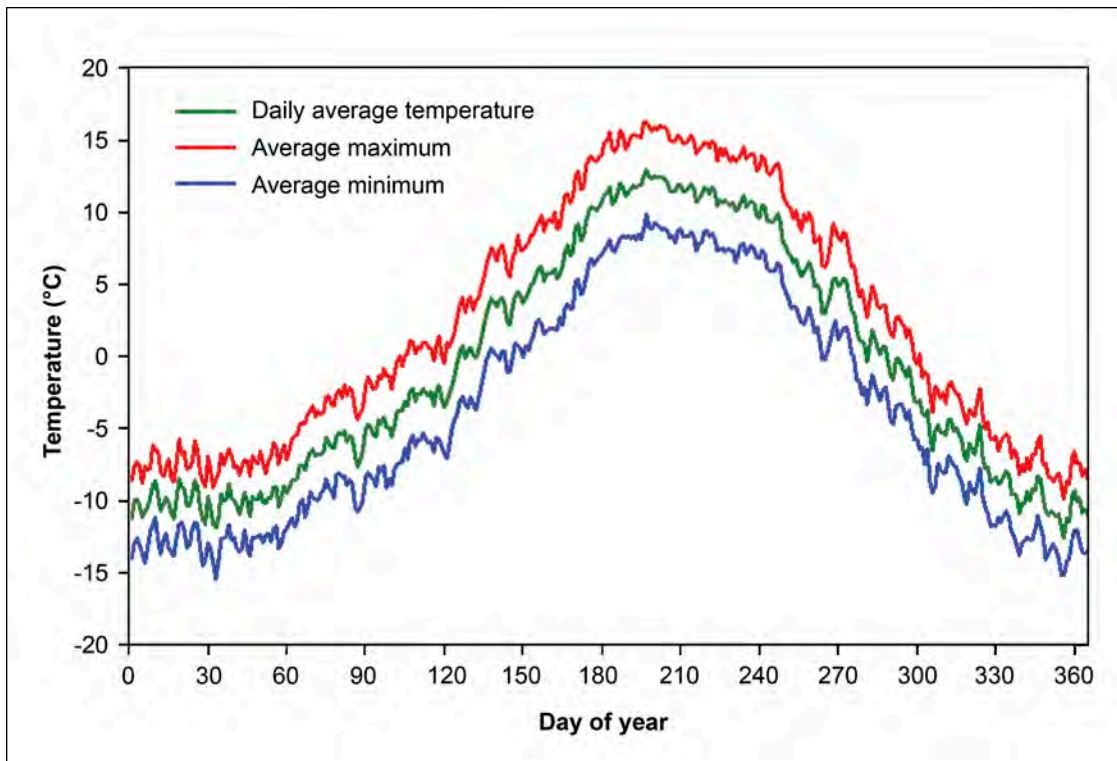


Figure 10.2—Average daily temperature ranges at Glacier Lake Ecosystem Experiments Site (GLEES), 1989–2014.

Stream discharge and water chemistry have been monitored since 1987 at four Parshall flumes located at the East Glacier Lake outlet stream, West Glacier Lake outlet stream, and Meadow Creek and Cascade Creek at their inlets to West Glacier Lake (fig. 10.1). Water chemistry was monitored at various depths at the deepest location in West Glacier Lake (9 m), East Glacier Lake (6.5 m), and Lost Lake (25 m), but this sampling was discontinued in the late 1990s. Dry and wet atmospheric deposition is monitored at three locations at GLEES (table 10.1): a Clean Air Status and Trends Network (CASTNet) site (Centennial 169) (1989 to present), and two National Atmospheric Deposition Program (NADP) sites, WY95 (1992 to present), and WY00 (1986 to present). The two NADP sites are near each other (fig. 10.1), with WY00 80 m higher in elevation than WY95, permitting comparison of deposition at two elevations. A Snow Telemetry (SNOTEL) site within GLEES has monitored snowpack depth and snow water equivalent since the 1930s, with data available electronically since 1980.

Availability of publications and data—

GLEES publications are available at the GLEES website (USDA FS 2016). As noted above, GLEES is part of several national networks, including NADP, CASTNet, AmeriFlux, and SNOTEL (table 10.1). Data from these networks are available from their websites. Meteorological and hydrological data are available from the Rocky Mountain Research Station data archive (USDA FS 2015).

Table 10.1—National monitoring networks that include the Glacier Lakes Ecosystem Experiments Site (GLEES) site^a

Monitoring network	GLEES sites	Attributes/analytes monitored	Frequency of sample or data collection	Duration of monitoring at GLEES	Network website
Clean Air Status and Trends Network	CNT169	Ozone, gaseous, and particulate chemistry (particulate: SO ₂ , SO ₂ ⁻⁴ , HNO ₃ , NO ₃ ⁻ , NH ₄ ⁺ ; base cations: Mg ⁺⁺ , Ca ⁺⁺ , K ⁺ , Na ⁺ , Cl ⁻)	Filter pack collected weekly for S, N, and cation and anion measurements; ozone recorded hourly	1989 to present	USDE 2017b
National Atmospheric Deposition Program (NADP) National Trends Network	WY95 WY00	In wet deposition: pH, SO ₄ , NO ₃ ⁻ , NH ₄ ⁺ , Ca ⁺⁺ , Mg ⁺⁺ , K ⁺ , Na ⁺ , Cl ⁻ ; reported as concentration and equivalents	Wet deposition samples collected weekly; precipitation recorded every 15 minutes	1992 to present 1986 to present	NADP 2019a NADP 2019b
Passive Ammonia Monitoring Network part of NADP)	WY95	Ambient NH ₃ concentration in dry deposition	Passive samplers collected and redeployed every 2 weeks	2007 to present	NADP 2019c
AmeriFlux	US-GLE	Micrometeorological measurements of ecosystem carbon dioxide (CO ₂), water vapor, sensible heat, and momentum fluxes; meteorology; soil water and thermal properties; stable isotopes of ¹³ C in CO ₂ and ² H/ ¹⁸ O in water vapor.	Micrometeorological data collected at 20 Hz, meteorological data collected every 5 minutes, AmeriFlux data product produced every 30 minutes.	1999 to present	USDE 2017a
Snow Telemetry	Brooklyn Lake No. 367	Precipitation (accumulated); snow depth; snow water equivalent; air temperature	Data from all sensors recorded hourly, and summarized for 3-hour intervals	1980 to present	USDA NRCS 2017

Particulates: SO₂ = sulfur dioxide, SO₂⁻⁴ = sulfate, HNO₃ = nitric acid, NO₃⁻ = nitrate, NH₄⁺ = ammonium; base cations are: Mg⁺⁺ = magnesium, Ca⁺⁺ = calcium, K⁺ = potassium, Na⁺ = sodium, Cl⁻ = chloride, S = sulfur, N = nitrogen.

^a For each network, raw data are summarized and modeled to increase detection of site, regional, and national trends, as described on the websites.

Biological Responses to Stream Nutrients N and P

Issues of Concern

The primary issue of concern for the WDEQ is providing for continued recreational enjoyment of unpolluted streams and lakes and maintaining high drinking water quality in the state's surface waters.

WDEQ is developing numeric nutrient criteria intended to protect Wyoming's streams, rivers, lakes, and reservoirs from excessive nitrogen (N) and phosphorus (P) pollution. Numeric nutrient criteria are intended to ensure a level of water quality that will protect assigned designated uses of these water bodies, such as fisheries, aquatic life other than fish, and recreation. The highest priority sites in Wyoming for collection of nutrient data are aquatic ecosystems that have the most potential for nutrient loading, such as those that receive agricultural runoff or discharge from municipal wastewater treatment plants. However, it will also be useful to have nutrient, phytoplankton and periphyton data from headwater streams and oligotrophic lakes that have few anthropogenic impacts, such as those at GLEES.

A potential source of N in high-elevation waters may be N deposition from air pollution generated by extensive oil and gas development upwind of GLEES since 1990. Oil and gas well permits increased dramatically in the western United States in the 1990s and early 2000s, but the development peaked in 2007. Wildland fires may also be a significant source of emissions of volatile N compounds during summer fire seasons. The size and intensity of wildland fires has increased in recent decades (McKenzie et al. 2004, Morgan et al. 2008) driven by regional drought and climate change. There is concern that N deposition from wildland fire may increase as climate warms in the future. Given that winds are predominantly from the west, deposition may also result from air masses moving from the Wasatch urban front in Utah and from an upwind coal-fired power plant west and upwind of GLEES.

Enrichment of lakes with N can cause algae blooms, a concern in waters used for recreation. Slight changes in nutrient levels have occasionally produced blooms of blue-green algae at West Glacier Lake. Many waters from alpine-subalpine basins in the Colorado Front Range are sources of drinking water for communities downstream. Increased N export from mountain areas can contribute to eutrophication of reservoirs and decrease the quality of drinking water.

Atmospheric deposition of N can contribute to acidity in surface water, especially in basins with low acid-neutralizing capacity. Acidity stresses fish and invertebrates in mountain streams and lakes, and at acute levels, can extirpate sensitive aquatic organisms such as trout.

Findings From Studies

Analyses of N wet and dry deposition since 1990 at GLEES (NADP 2019a, 2019b, 2019c) indicated no significant increases in N deposition at the site. Since 1989, East Glacier Lake has had a small but significant decrease in nitrate (NO_3^-) output (Dwire, n.d.), although N output from West Glacier Lake has not significantly changed over the period.

Baseline condition of the aquatic biotic communities in GLEES lakes was well characterized with checklists and densities of phytoplankton and zooplankton (Musselman 1994). Limited periphyton data are available for the West Glacier outlet stream. In small lakes and ponds without fish, we have also documented occurrence of a rare fairy shrimp species (*Branchinecta paludosa*), not reported in North America outside of Alaska and Canada (Belk et al. 1993). The study lakes have been stocked with cutthroat trout (*Oncorhynchus clarkii* Richardson), nonnative brook trout (*Salvelinus fontinalis* Mitchell), and rainbow trout (*O. mykiss* Walbaum) (see under “Responses to Management and Natural Disturbances”).

Other Factors Relevant to Stream Nutrients N and P

Meteorological data, including soil and air temperature, relative humidity, solar radiation, windspeed, and wind direction (fig. 10.3), have been collected at GLEES since the late 1980s (Musselman 1994). Several other long-term monitoring datasets have been collected at GLEES as part of national networks (table 10.1).

Air temperature has significantly increased during summer (July to September) in the two decades of meteorological monitoring at GLEES (USDA FS 2015), but no long-term record of water temperature has been collected.

West Glacier Lake inlets and outlet have seasonal streamflow patterns with implications for N export. Winter streamflow is characterized by very low inflows from a few springs, and lake outflow ceases when the outlet stream freezes. During winter, the West Glacier Outlet stream receives a trickle of flow several hundred meters downstream of the lake outlet from emerging subsurface flow and springs. Surface flow in West Glacier Outlet stream resumes as snow melts in early May.

Stream chemistry shows a pulse of N and acidity at snowmelt initiation, and N export at the lake outlet during snowmelt indicates that rapid lake turnover exceeds the capacity of the aquatic biota to absorb increased available N entering the lake (Ruess et al. 1995). The source of the increased N is NO_3^- deposited in winter snow and stored in the snowpack. Most of the stored NO_3^- is released in the early period of snowmelt when N is preferentially eluted. At mid-summer, lakes receive lower inflows and show algae blooms, with Secchi depths less than 2 m. In that period,

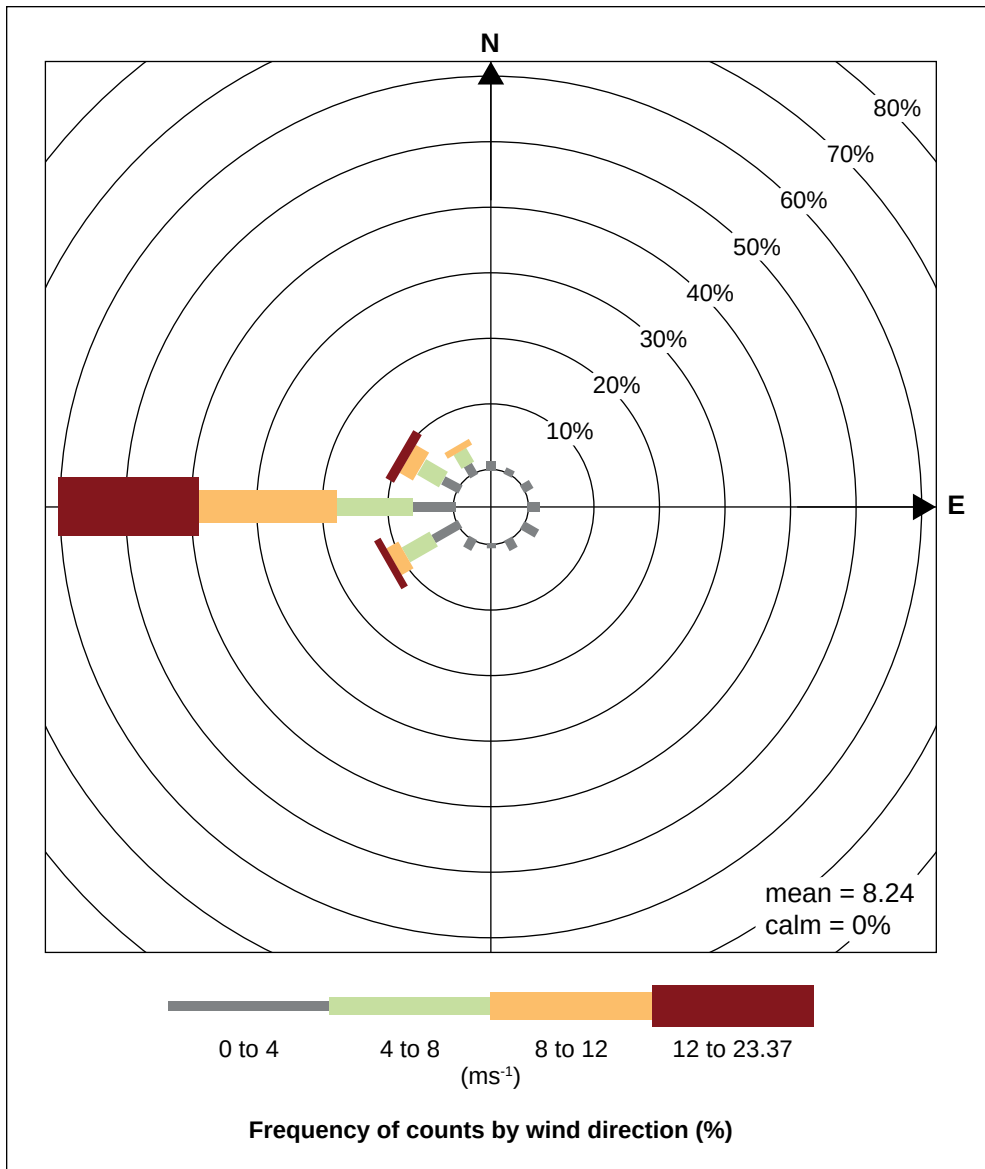


Figure 10.3—Wind rose showing predominant westerly wind direction. Much of the more recent oil and gas development is located to the east and north of the Glacier Lakes Ecosystem Experiments Site.

NO_3^- is utilized by increased growth of phytoplankton. September and October N concentrations at the outlet are below detection levels, suggesting the lake is not N saturated at this time of year. These seasonal patterns are repeated each year, although the timing of initiation of snowmelt, the amount of flow, and the magnitude of a spring pulse in NO_3^- concentration vary depending on the size of the winter snowpack and the timing of spring temperatures.

Reference Watersheds

GLEES is managed as an undisturbed watershed, with no tree harvesting permitted, and it is considered a reference watershed. Disturbance of soil or vegetation by management activities is only allowed to protect public safety. Before establishment of GLEES, selective timber cutting occurred prior to 1930, and some small, abandoned mining pits indicate past mineral extraction (Thybony et al. 1986). Grazing of sheep was heavy in the 1930s and tapered off until the 1990s when grazing permits were discontinued (Musselman 1994). Tree invasion of subalpine meadows has increased since grazing was removed, although it may also be a response to warming climate (Moir et al. 1999).

GLEES and the surrounding area receive recreational use for hiking, camping, and fishing in summer and snowmobiling and backcountry skiing in the winter. Recreational disturbance to vegetation and soils is generally confined to trails and edges of lakes. Recreation use has increased significantly since the 1980s, but is still considered to be light with minimal impact on surface waters.

Brooklyn Lake is located downstream of most GLEES streams and lakes that have been regularly monitored for water chemistry. This lake has about a dozen permitted, seasonally occupied, shorefront cabins with septic systems. Water chemistry data from the outlet of Brooklyn Lake since 1994 has shown that NO_3^- has not exceeded 1 mg/L at baseflow in September, suggesting that septic leaching has had minimal impact on water quality.

GLEES probably represents conditions in lakes and streams in wilderness and other relatively undisturbed areas near tree line in the Front Range. With the exception of permanent research instrumentation, deviations from wilderness management have been minor and are similar to activities in many backcountry, high-elevation areas in the region.

Responses to Management and Natural Disturbances

Similar to most wilderness areas in the southern Rockies, GLEES lakes have historically been stocked with nonnative cutthroat, brook, and rainbow trout. Although originally fishless, West Glacier Lake, East Glacier Lake, Lost Lake, Brooklyn Lake, Little Brooklyn Lake, and the Telephone Lakes were stocked beginning in the 1930s or 1940s. Stocking was discontinued in lakes with self-sustaining trout populations. Brooklyn Lake continues to be stocked annually, and East Glacier Lake is stocked every other year. Detailed stocking records are available from the Wyoming Game and Fish Department or from the authors. This fisheries management likely has altered aquatic communities and food webs in these lakes, but these potential effects have not been studied.

Spruce beetles have recently infested Engelmann spruce trees in subalpine forests throughout the southern Rocky Mountain region, including the GLEES. Since 2008, researchers have been studying the effects of beetle-caused canopy mortality on ecosystem processes near the AmeriFlux tower (fig. 10.1) (Frank et al. 2014) and on understory vegetation. Although forest harvest is not allowed within GLEES, removal of selected trees is planned along the Brooklyn Lake Road (fig. 10.1) for safety reasons. The immediate impacts of tree loss on ecosystem carbon and water fluxes will be monitored at the AmeriFlux tower, while the effects of canopy mortality on vegetation succession will be investigated over coming decades. Effects of tree mortality on stream nutrients or aquatic communities have not been studied.

Dose-Response Studies

Dose-response studies have not been conducted at the GLEES.

Cross-Site and Regional Studies

Data on deposition of N from NADP and CASTNet monitoring at GLEES have been used in regional and national analyses of atmospheric deposition that are periodically updated (Baron et al. 2011; Burns 2003, 2004). Data from GLEES are also regularly incorporated in SNOTEL regional snow cover and snowpack summaries and water supply forecasts.

Reliability and Limitations of Findings

Findings from GLEES could be expected to apply to other high-elevation catchments in the southern Rocky Mountains with similar geology and terrain features. At sites where elevation, geology, wind dynamics, snow distribution, or aspect, differ from GLEES, or where a high degree of accuracy is required, we suggest validation studies or monitoring to test how well the GLEES findings represent conditions elsewhere in the region.

Research Needs

The highest priority research need that could be filled at GLEES, from the perspective of the regional water quality regulatory community, is more recent, detailed limnologic water column data, including water chemistry, at the GLEES lakes. These data would be useful to water quality regulatory agencies for the development of nutrient criteria for oligotrophic lake systems. Although such data were collected at GLEES from 1989 to 1999, they may be outdated. More recent observations are needed to assess current conditions. This need could be filled by resuming regular monitoring of detailed water column nutrient concentrations at several depths at the deepest location in the GLEES lakes.

Other research needs that could be filled at GLEES, but of lower priority to the regulatory community, include the following:

- Understanding the level of atmospheric deposition of N that would exceed critical thresholds of nutrient enrichment that cause undesirable biological responses in high-altitude lakes. Critical N deposition loads have been published for high-elevation lakes elsewhere in the Western United States (Baron 2006, Nanus 2012, Saros et al. 2011), but their applicability to GLEES needs to be validated.
- Impacts of climate change on water temperature, snowmelt, streamflow, and stream chemistry.
- Potential interactive effects of climate warming and N deposition on lake water quality and primary productivity.
- Impacts on water quality of wilderness recreational use, particularly in the summer.
- Responses of algal populations to changes in N levels in high-altitude lakes.

Potential Utility to Water Quality Regulatory Agencies

The 25-year database of baseline hydrological, biological, and meteorological record for first-order, surface-water catchments at GLEES could be useful to the WDEQ for water quality criteria development, total maximum daily load (TMDL) modeling, and determination of trends in high-elevation surface water quality. Similar databases are generally lacking for development of WDEQ nutrient criteria. Based on regional assessments, GLEES can be considered a relatively undisturbed, reference watershed (Baron et al. 2011, Nanus et al. 2012). Because most pollutants associated with land use have been controlled at GLEES, long-term changes in surface-water chemistry from atmospheric deposition or climate change are more likely to be detected there. This relatively undisturbed area with no nearby agricultural or urban emissions and with minimal previous impact from atmospheric deposition from energy development, is especially useful for numeric nutrient criteria development.

Data of interest to the WDEQ for development of nutrient criteria for lakes include alkalinity (as calcium carbonate [CaCO_3]), conductivity, ammonium (NH_4^+), NO_3^- , nitrite (NO_2^-), total N, dissolved oxygen, oxidation reduction potential, P, water temperature, chlorophyll a, phytoplankton species and biomass, Secchi depth, and geographic positioning system location of the data source. Because WDEQ has collected little data from alpine lakes, data collected from the GLEES, using WDEQ-approved standard operating procedures and quality assurance/quality control, would contribute to development of nutrient criteria in mountain ecoregions.

Although these data are available for East and West Glacier Lake at GLEES, similar data from the outlet streams at GLEES is limited, except for the West Glacier outlet stream. Both the West Glacier and East Glacier outlet streams are less than 500 m in length and flow into Brooklyn Lake, which is the source of the Nash Fork of the Little Laramie River. Monitoring these additional streams and lakes at GLEES would be of interest to regulators because they are the headwaters of the Laramie River, which is a tributary of the North Platte River. WDEQ might consider collaborating with the U.S. Forest Service to add these GLEES sites to its statewide water quality monitoring network.

Key points:

- The GLEES physical and biological monitoring serves as a valuable resource for the WDEQ in the development of nutrient water quality criteria for oligotrophic aquatic ecosystems, a high research priority from the perspective of the regulatory community.
- Data collected at GLEES might also contribute to determination of the level of water quality necessary to protect the designated uses of these surface waters, including fisheries, other aquatic biota, and recreation.
- Studies at GLEES might be useful to investigate in high-altitude lakes what levels of N atmospheric deposition would exceed critical thresholds of nutrient enrichment that cause undesirable biological responses.
- Environmental datasets from GLEES could also be used by regulatory agencies for practical purposes such as water quality criteria development, total maximum daily load modeling, and measurement of trends in high-elevation surface water quality.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Sulfur (S), in the form of sulfate (SO_4^{2-}), is a primary constituent of atmospheric deposition from fossil fuel combustion upwind of the Medicine Bow Mountains. High-elevation streams and lakes could be acidified if the combined deposition of SO_4^{2-} and N increased to exceed the low acid-neutralizing capacity of these sensitive water bodies. Aquatic plants, including phytoplankton, and fauna, especially fish and invertebrates, could be negatively affected by lake and stream acidification. Loss of aquatic biota may detract from users' wilderness experience and recreational fishing opportunities. Wilderness lakes and streams that become altered by pollutants might no longer be perceived by the public as pristine.

Fossil fuel combustion upwind of the Snowy Range from electric generation power plants, drilling rigs, pumps and field processing of oil and gas generate airborne S compounds, particulates, and toxic organic compounds. These compounds are also generated locally by vehicle traffic and snowmobiles. The impact of deposition of these chemicals on downwind ecosystems and surface waters, especially in wilderness areas, is unknown. Increased S and toxics in surface waters from deposition are a primary concern as their impact on drinking water and fisheries in these headwaters is unknown.

Findings Related to Stream Nutrients Other Than N and P

Surface water monitoring at the four Parshall flumes has been conducted seasonally from early May through mid-October since the late 1980s. Water samples collected have been analyzed for pH, conductivity, alkalinity, cations, including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+), and anions, including fluoride (F^-), chloride (Cl^-), and SO_4^{2-} . Stream chemistry at West Glacier Outlet has had a small but significant increase in Na^+ , Ca^{2+} , and acid-neutralizing capacity since 1989 (Dwire, n.d.).

Other Factors Relevant to Stream Nutrients Other Than N and P

Extensive research has been conducted at GLEES on ecosystem carbon (C) stocks and fluxes, water fluxes, and heat and energy exchange. The C stock in biomass at GLEES is about 330 Mg C/ha, higher than at other Rocky Mountain Front Range alpine/subalpine study sites at Fraser Experimental Forest (see chapter 9) and Niwot Ridge in Colorado (Bradford et al. 2008). Recent studies have found that forest overstory mortality from bark beetles has increased albedo and sensible heat flux, and reduced evaporation and net C exchange at GLEES (Chen et al. 2014, Frank et al. 2014).

Reference Watersheds

As was described earlier, regular monitoring of nutrients other than N and P, has been conducted on streams in reference watersheds because all of the monitored watersheds at GLEES are functionally reference watersheds.

Response to Management and Natural Disturbance

GLEES is managed similarly to U.S. Forest Service wilderness ecosystems, including the prohibition of manipulations of vegetation or soils. Despite tight controls of on-the-ground human disturbances, effects of regional and global influences, such as weather modification, are unavoidable.

To test the feasibility of artificially augmenting precipitation, the state of Wyoming, and its partners, recently injected silver iodide (AgI) crystals into the

atmosphere in a 6-year cloud seeding pilot study, conducted in the Snowy Range (Breed et al. 2014). GLEES and its surrounding areas were in the zone affected by the regional experiment. Silver (Ag) is a metal that is potentially toxic to plants and animals. Modeling analyses (WWMP 2014) found that Ag input to the ecosystem from cloud seeding was likely negligible because it was equivalent to only a small fraction of ambient Ag already present. Increases in deposition of N, S, and other nutrients were also expected to be small because precipitation was predicted to increase by 5 to 15 percent. The experiment was expected to increase streamflow 0.4 to 3.7 percent (WWMP 2014). Routine monitoring of precipitation, streamflow, snowpack, atmospheric deposition of N and S, and stream export of N and S were conducted at GLEES during the cloud seeding pilot. However, these GLEES data were not collected to detect effects of the pilot and have not been analyzed for that purpose. For example, neither silver nor iodide were monitored in precipitation at GLEES. Potential effects of beetle-caused tree mortality on stream nutrients other than N and P have not been studied.

Dose-Response Studies

Dose-response studies have not been performed at GLEES.

Cross-Site and Regional Studies

Data on deposition of SO_4^{2-} , Cl^- , Na^+ , K^+ , Ca^{2+} , Mg^{2+} , and hydrogen ion from the NADP monitoring at GLEES, plus ozone (O_3) and sulfur dioxide from CASTNet monitoring, have been used in regional and national analyses of atmospheric deposition (Baron et al. 2011; Burns 2003, 2004; Nanus et al. 2013) that are periodically updated and available on those network websites.

Reliability and Limitations of Findings

The same limitations of findings that apply to N and P studies at GLEES also apply to studies on other nutrients.

Research Needs

The highest priority research question of the regulatory community, related to nutrients that might be answered at GLEES is, What would be the impacts on high-elevation surface waters and aquatic biological systems in the Rocky Mountain Front Range if acidifying effects of atmospheric deposition of SO_4^{2-} and N were to increase? This information is potentially important for regional water quality regulatory agencies because it would provide a scientific basis to anticipate what changes in water chemistry are likely to occur if the combined effects of atmospheric deposition of SO_4^{2-} and N increased the acidity in high-elevation

surface waters and what biological responses might accompany those water chemistry changes. Future research to answer these questions at GLEES would include resumption of monitoring limnologic water column data at the GLEES lakes; additional monitoring of water chemistry in the GLEES outlet streams, such as Nash Fork below Brooklyn Lake; and experiments or monitoring to determine what taxa would be sensitive in surface waters to the acidifying effects of increased atmospheric deposition.

Another question of regulatory interest, but of lower priority, would be, What are the effects of long-term climate change on nutrients other than N and P and biological responses to them in high-elevation lakes in the Front Range?

Potential Utility to Water Quality Regulatory Agencies

Long-term monitoring datasets from GLEES of atmospheric deposition and high-altitude stream and lake water concentrations of SO_4^{2-} and N might be useful for including potential effects of acidification driven by atmospheric deposition of air pollutants in water quality criteria development, TMDL modeling, and determination of temporal trends in high-elevation surface-water quality.

Key points:

- GLEES has extensive long-term datasets of atmospheric deposition and high-altitude stream and lake water concentrations of SO_4^{2-} and other nutrients other than N and P.
- These data are potentially useful to water quality regulatory agencies for developing water quality standards, TMDL modeling, and determining temporal trends in water quality in high-elevation lakes and streams.
- The highest priority research need that could be filled at GLEES on this topic is, What impacts on high-elevation surface waters and aquatic biological systems in the Rocky Mountain Front Range could result from increases in acidification owing to atmospheric deposition of SO_4^{2-} and N?

Overview and Synthesis

GLEES is a relatively undisturbed and well-studied high-elevation site downwind of considerable energy development. Prevailing westerly winds carry emissions to GLEES from energy development in central Wyoming and northern Colorado, but less frequent easterly winds also carry emissions. Although emissions such as nitrogen oxides, volatile organic compounds, and O_3 from energy development have been well monitored and modeled in Wyoming upwind of GLEES, little is known about their ecological effects on high-elevation ecosystems such as GLEES. Glacier

Lakes Ecosystem Experiments Site monitoring data have spanned the period of recent expansion in energy development and could be analyzed for temporal trends. Because land uses that might confound effects of air pollution have been controlled at GLEES, it is well-suited for detection of deposition of N and S compounds and toxic organic chemicals from oil and gas development, and their ecological effects on high-elevation surface waters.

The existing GLEES database is potentially useful to the WDEQ to examine long-term change in mountain ecosystems and surface waters to climate change. No other database in Wyoming provides comparable detailed long-term information on high-elevation surface waters, or has the potential to detect changes over time in response to a warming climate.

Key points:

- GLEES is a high-elevation research site with extensive baseline data of meteorology, water chemistry, hydrology, and aquatic and terrestrial biology that can be used by the Wyoming Department of Environmental Quality.
- These data are most relevant for detecting the effects of atmospheric deposition of N, P, S, and other chemicals on surface water quality and aquatic resources in high-altitude headwater ecosystems.
- The highest priority science needs of the regulatory community that could be filled at GLEES are (1) the long-term collection of limnologic water column data, (2) the biological responses in high-elevation waters to enrichment by the nutrient N, and (3) the acidifying effects of both S and N if these elements were to increase in atmospheric deposition.
- The spatial location of GLEES is important for regional detection of increasing global change and atmospheric deposition effects. There are no other long-term monitoring sites at this high elevation in Wyoming.

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Chapter 11: Ecoregion 7.1.8 Coast Range: Caspar Creek Experimental Watersheds, California

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Introduction

This chapter is a review and synthesis of research conducted at the Caspar Creek Experimental Watersheds (CCEW) on stream nutrients and their responses to forest management. Results from relevant scientific studies conducted at CCEW are provided, as well as a description of future potential research. This information is relevant to water quality regulatory agencies.

Site Description

CCEW are located at lat. 39° 21' N, long. 123° 44' W (fig. 11.1), between 5 and 10 km from the Pacific Ocean on the western slope of the northern California Coast Ranges, in the western portion of Jackson Demonstration State Forest. The land within the experimental watersheds is owned by the state of California and is administered by California Department of Forestry and Fire Protection (CAL FIRE). The 473-ha North Fork and 424-ha South Fork watersheds span an elevation of 30 to 322 m. Both watersheds are underlain by shales and sandstones of the Coastal Belt of the Franciscan Complex, which have developed sandy to gravelly loam soils, often with clay to clay-loam subsoils. The main stem channels are gravel bedded and have incised slightly into narrow former floodplains. Tributary channel profiles are broken by frequent headcuts.

Climate is moderate at the site, with a mean December minimum temperature of 4.9 °C and a mean July maximum of 21.4 °C. Mean annual rainfall is nearly 1200 mm, ranging from 400 to 2202 mm over the 54-year monitoring period. Snow is hydrologically insignificant. Rainfall is strongly seasonal, with 95 percent occurring in October through May, and tributaries draining areas <20 ha are generally dry by June. Summer fog is common. Fog drip can account for as much as 3 percent of annual rainfall on exposed ridgetops, but drip rates are considerably lower elsewhere in the watersheds (Keppeler 2007).

The original old-growth forest, dominated by coast redwood (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), was clearcut between about 1860 and 1904. By 1961, the second-growth forest, composed of the same species, averaged 85 years old in the South Fork and about 20 years younger in the North Fork. Timber production has been the primary land use at the site.

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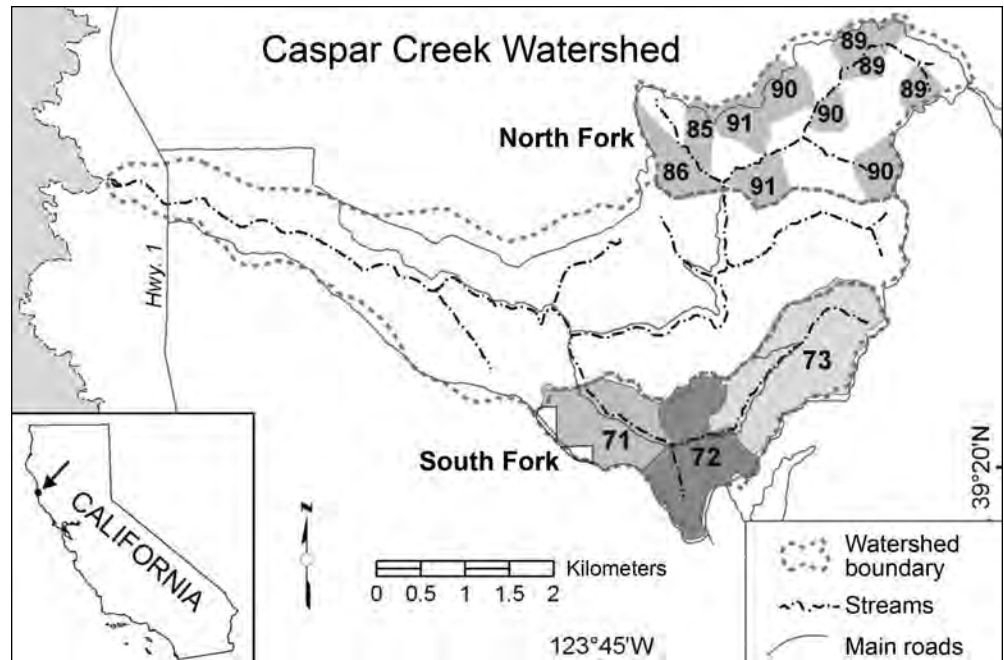


Figure 11.1—North Fork and South Fork Caspar Creek Experimental Watersheds. Numbers indicate the years that shaded areas were logged for the second time. Old-growth forests were first logged from approximately 1860 to 1904. This coastal watershed discharges into the Pacific Ocean.

Research History

In 1961, the U.S. Forest Service (USFS) Pacific Southwest Research Station and CAL FIRE entered into a cooperative agreement to study the effects of logging on water quality, flooding, and salmonid resources at Caspar Creek. The initial CCEW watershed experiment employed the North Fork as a reference watershed to study the effects of road construction in 1967 and tractor-yarded selection logging during 1971–1973 in the South Fork, with effects on streams monitored at basin-mouth weirs. Timber operations were carried out using practices characteristic of the period immediately preceding institution of modern forest practice regulations in California.

The second CCEW watershed experiment was designed to evaluate cumulative watershed impacts and was carried out in accordance with forest practice rules in use at the time. Gaging began in late 1985 at 13 nested gaging stations in the North Fork watershed. Three North Fork tributaries were selected as unmanaged, reference watersheds, and 37 percent of the watershed was clearcut logged and yarded, primarily by skyline cable, between 1989 and 1992. Logging debris was broadcast burned on 19.5 percent of the watershed area in 1990–1991.

A third major set of logging treatments, called CCEW Experiment Three (USDA FS 2016c), is now being implemented in the South Fork. This study is

evaluating effects of reducing stand density from zero to 75 percent in eight subwatersheds on sediment yields and their sources, peak flows, water movement from hillslopes to channels, low flows, water temperature, macroinvertebrates, subsurface moisture dynamics, and stream nitrogen (N), phosphorus (P) and a wide array of other nutrients. Prelogging monitoring of total nutrient loads of four study subwatersheds has been completed (Dahlke et al. 2018), and export of dissolved N and P has been measured for 10 storm events between October 2016 and May 2017. Timber harvesting in the South Fork began in June 2017.

Availability of publications and data—

Many of the datasets collected for the watersheds (table 11.1) are available on the CCEW website (USDA FS 2016a), or from Pacific Southwest Research Station or CAL FIRE by request. Daily streamflow and meteorology may be downloaded in formats that permit comparisons with other experimental forest and ranges (EFRs) and long-term ecological research (LTER) sites at the ClimDB/HydroDB website (LTER Network 2013). Ziemer (1998b) summarized methods and results for the experiments, and CAL FIRE (2005) described the natural and human setting in the area. Cafferata and Reid (2013) reviewed CCEW results and described how the information has been applied by regulatory agencies. Morken and Ziemer (1998) and Reid (n.d.) provided annotated bibliographies of CCEW publications. Most publications are available on the CCEW website (USDA FS 2016b) or on those of cooperating agencies.

Biological Responses to Stream Nutrients N and P

Issues of Concern

Beneficial water uses of high concern in the region include threatened and endangered species, especially anadromous salmonids, domestic water supply, freshwater habitat, and water contact recreation. The North Coast Regional Water Quality Control Board found that most waters draining primarily forested watersheds in this region have only temperature and sediment impairments (NCRWQCB 2014), and none are listed for nutrient loads related to silviculture. Nutrient loads impair six waterbodies, all of which drain significant urban or agricultural areas.

Although forest lands are not identified as a source of excess nutrient loads in the region, forestry activities can affect downstream loads by altering streamflow, sediment, riparian forest composition, and stream temperature, which, in turn, affect nutrient transport. Where forest lands are located in watersheds with agriculture or urban areas, runoff from forests dilutes nutrient inputs from those areas. In such settings, increased nutrient output from forests, or conversion of forest land

to other uses, might contribute to a cumulative downstream nutrient impact by reducing the effectiveness of dilution, even if nutrient outputs from the forested or converted watershed remain below prescribed limits.

Maintenance of productive forests is a high priority in the region because of their economic importance. Currently, fertilizers are rarely used on the region's forests, but cumulative nutrient depletion could prompt increased application, leading to increased stream nutrient loads. If fertilizers are not applied and N fixers such as those associated with *Ceanothus* spp. are suppressed with herbicides to reduce competition for young conifers, depletion could modify long-term site productivity and also affect nutrient loads. Past riparian logging has altered

Table 11.1—Principal datasets collected at Caspar Creek

Category	Attribute	Comments
Climate	Solar radiation	1965–1968, 1988–present, various periods and sites
	Air temperature	1967–1968; 1989–present, various periods and sites
	Humidity	2001–present, various periods and sites
	Windspeed	1998–2001, 2009–present
Hydrology	Rainfall	1961–present, various periods and sites, two continuous
	Fog drip	1998–2001; 2012–present, multiple sites and methods
	Throughfall	1998–2001, two sites, 2006–2010, two sites
	Stemflow	1999–2001, 24 trees
	Soil pipeflow	Various periods, 1986–present, four sites
	Streamflow	1962–present, 25 sites various periods, weirs (NF and SF)
Water quality	Chemical constituents	1968–1969, 1991–1996, 2003–2005, 2016–present, various components
	Dissolved oxygen	1968–1969; monthly 1989–1990, four measurements
	pH and conductivity	1968–1969, monthly 1989–1990, NF 1991–1996, four measurements
	Stream temperature	1963–1969, 1988–present (NF), 1998–present (SF), various periods at 11 sites
	Turbidity	Occasional before 1996; continuous at multiple stations since then
	Nutrients	1991–1996, 13 sites (NF); 2016–present, 5 sites, (SF)
Soils	Hydraulic conductivity	Multiple sites
	Piezometric pressure	1987–present, four sites, various periods
	Soil moisture	1987–present, four sites, various periods
	Soil temperature	2011–present, two depths
Erosion	Landslides	1986–present (NF), 2001–present (SF), Annual stream maps
	Plot inventories	1975 SF, 1996 NF
	Road surface erosion	2005–2007, measurements at culverts; 2018–2019
	Headcuts and gullies	2000–present, occasional remapping
	Pipe erosion	1989–1993, pump samples during storms, coarse in wire baskets

Table 11.1—Principal datasets collected at Caspar Creek (continued)

Category	Attribute	Comments
Stream sediment	Concentration	1962–present at each gage; pump samples and depth integrated
	Suspended sediment load	1962–present, various periods at 27 stations
	Bedload	1978–1980 manual samples; 1987–1997 pit sampler; one site
	Organic load	2002–2003
	Sedimentation	1962–present, annual bathymetric survey of weir ponds
	Sediment grain sizes	1986–1993 pebble counts; 1987–1997 pit samples; 1967–1969 McNeil samples
	V-star (pool infill)	1991–present, measured annually until 2012, then every 2 years
Channel condition	Woody debris	1986, 1994, 1996; since 1998 tagged logs mapped every 2 years
	Cross sections	1979–present (NF), 2000–present (SF), every 2 years
Aquatic biota	Redd surveys	1990–1992; 2000–present
	Downstream migrants	1964, 1968, (NF and SF); 1986–1988, 2000–present
	Upstream migrants	1963–1964 (NF and SF), 2000–present
	Rearing salmonids	1967–1969, 1986–1995 (NF and SF), 2000–present
	Salamander biomass	1986–1995, Pacific giant salamanders; electrofishing
	Macroinvertebrates	1965–1969, 1987–1994, 2002–2003, 2016–present
	Leaf decay	1988–1993, leaf packs; autumn measurements; three sites, (NF)
	Algae growth	1987–1994, tiles; 15 sampling dates, 5 sites, (NF)
Terrestrial biota	Growth and yield	1958–present continuous forest inventory plots measured every 5 years
	Nutrient content	2012–2013, element concentrations in conifers; two sites
	Seral development	1982–1983, 1990–1993; plots with a gradient of clearcut ages
	Riparian treefall	1998–present, every 2 years

NF = North Fork, SF = South Fork.

instream productivity, and recent reductions in anadromous fish runs contribute to altered nutrient cycling in riparian zones by reducing marine nutrient inputs from returning salmonids. Conversion of forest lands to urban development and agriculture, primarily vineyards, can lead to significantly increased nutrient loads. Cannabis (*Cannabis sativa* or *C. indica* (Lam.) E. Small & Cronquist) cultivation, a multibillion dollar industry, affects forest land in the area by degrading water quality through use of fertilizers and pesticides (Bauer et al. 2015, Butsic and Brenner 2016, NCRWQCB 2013). Water contact recreational uses in the region are affected by toxic blue-green algae blooms, which are promoted by high temperatures, low flows, and high nutrient loads.

Findings From Studies

Overall N and P conditions—

Measurements of instream nitrate (NO_3^-) under forested conditions at CCEW (Bottorff and Knight 1996, Dahlgren 1998a, Kopperdahl et al. 1971) show concentrations generally lower than the median value reported for forested streams elsewhere in the United States (Binkley et al. 2004). Streamwater in CCEW reference watersheds usually had NO_3^- concentrations less than the detection limit (0.02 mg/L as NO_3^-) and had a maximum observed concentration of 0.7 mg/L (as NO_3^-) during storms. The USEPA (2000) reference condition value for ecoregion 1 (Coast Ranges) is 0.09 mg/L, and the level for eutrophication concern is 1.3 mg/L (Roche et al. 2013). Dahlgren (1998a) evaluated N pools in biomass and soils in a North Fork reference watershed and measured NO_3^- concentrations in streamflow, rainfall, throughfall, soil solution, and pipeflow, which is bulk transport through naturally occurring conduits in the soil called soil pipes. Annual flux in streamflow from the watershed averaged 0.025 kg N/ha for the 5-year period.

Similar analyses for P were performed and foliage was found to enrich P concentrations in throughfall. Annual P flux in streamflow averaged less than 0.0014 kg/ha, and orthophosphate (PO_4^{3-}) concentrations ranged between undetectable and 0.1 mg/L. Measurements of PO_4^{3-} concentrations in streamflow were similar to those reported by Binkley et al. (2004) for other western conifer forests. Natural undisturbed forest background stream water concentrations for PO_4^{3-} usually range from 0.005 to 0.05 mg/L (Dunne and Leopold 1978), and the level for eutrophication concern is 0.15 mg/L as PO_4 (Roche et al. 2013).

Riparian zones in the area receive annual inputs of marine-derived P and other nutrients through immigration of adult anadromous salmonids. Moore et al. (2011) found that recent reductions in salmonid populations have reduced P imports to the region's streams to the point that the annual flux may be shifting to net export by outmigrating immature salmonids.

Effects of N and P: organismal responses—

Many CCEW studies have focused on salmonids and other aquatic biota (table 11.1). Reports from early CCEW experiments documented salmonid conditions in the North and South Forks (Graves and Burns 1970, Kabel and German 1967). Hess (1969) measured the rate of insect infall from the riparian zone at stations along the South Fork in 1966 and 1968 and summarized benthic macroinvertebrate samples from the North and South Forks. Burns (1971) found no relation between P measurements and salmonid biomass at Caspar Creek and several other streams and concluded that other habitat influences were more important.

Although biological results during the North Fork experiment were not analyzed directly with respect to nutrient levels, they may be used to characterize biological conditions under the nutrient cycling regime present in the 1990s. Nakamoto (1998) found large variations in juvenile coho salmon (*Oncorhynchus kisutch* Walbaum) and steelhead trout (*O. mykiss* Walbaum) biomass during the period in which nutrients were monitored. Harvey and Nakamoto (1996, 1997) experimentally manipulated juvenile populations within enclosures in both the North and South Forks to examine interactions between these two species. Monitoring of larval Pacific giant salamander (*Dicamptodon tenebrosus*) showed increasing numbers between 1991 and 1996 in the North Fork, but no clear trend in the South Fork (Nakamoto 1998).

Bottorff and Knight (1996) identified benthic macroinvertebrates colonizing rock packs emplaced along the North Fork between 1987 and 1994. Downstream stations had significantly higher densities of macroinvertebrates and more taxa present than upstream stations. The study also found rapid instream alder leaf decomposition rates in emplaced leaf packs, and, in one case, the measured decay rate (k) of 0.0912/day exceeded the highest published rate. Bottorff and Knight (1996) also measured chlorophyll a (chl a), assessed algal biomass, and identified and counted diatoms on emplaced clay tiles. Chl a levels and algal biomass were significantly higher in fall and increased downstream.

Additional instream biological work was carried out after nutrient monitoring ended. Gallagher et al. (2010, 2013) described results of intensive monitoring of various life stages of anadromous salmonids in the Caspar Creek watershed, which documented a decline in coho salmon populations. This trend was not as evident in 1993–2003, when Valentine et al. (2007) found that populations of juvenile salmonids in the South Fork were within the range reported by Burns (1971) for 1967–1969.

To study the effects of particulate organic sediments, Wilzbach et al. (2009) evaluated algal chl a in the suspended load, benthic and drift macroinvertebrates, salmonids, and microbial respiration in the North and South Forks during six periods in 2002–2003. Overall, suspended organic particles influenced instream attributes in ways similar to nonorganic components of the sediment load.

Control of nutrient dynamics by stream and watershed processes—

Dahlgren (1998a, 1998b) found that NO_3^- concentrations increased with increasing streamflow during storms, suggesting that the source of NO_3^- -bearing inflow differs for stormflow and baseflow. Stormflow is likely to be supported more by shallow subsurface flow through the NO_3^- -rich A and AB horizons, while baseflow originates from deeper zones (O'Geen et al. 2010, Swarowsky et al. 2012). Sedimentary rocks in CCEW contain significant N, so some of the NO_3^- in streamflow may originate from bedrock weathering (Morford 2015).

Studies of Other Factors Relevant to Stream Nutrients N and P

Many physical and biological conditions that can affect nutrient cycling in forested watersheds have been evaluated at CCEW (table 11.1). Henry (1998) described many of the monitoring methods used. Rainfall monitoring began in the watersheds in 1961, and other climatic data collected at various times include windspeed, solar radiation, relative humidity, throughfall, fog drip, and air temperature. Fog drip was found to contribute little moisture over most of the watershed (Keppeler 2007), and data showed a loss of 22 percent of rainfall to evaporation of foliar interception in second-growth stands (Reid and Lewis 2009). Subsurface hydrology has been monitored in a second-growth watershed, a clearcut watershed, and along a slope transect across a logging road (Keppeler and Brown 1998). Monitoring demonstrated the importance of soil pipes as a source of stormflow (Albright 1992).

Streamflow monitoring has been a fundamental aspect of the CCEW studies since the project began in 1961. Thirteen additional gaging stations were installed in the North Fork in 1985, and 10 more in the South Fork in 2000. Keppeler (1998) described water yield results and evaluated dry-season flows using records from the weirs and from instream wells installed near tributary gaging stations. After timber harvesting, increased water yields and summer flows were documented at the weirs for both the North and South Forks of Caspar Creek.

Sediment is a second major focus of CCEW research (Lewis 1998). Sediment load estimates were originally based on sediment rating curves, but the Turbidity Threshold Sampling protocol was developed for the watersheds in 1995 (Lewis and Eads 2009), and loads for subwatersheds are now estimated using calibrated 10-minute turbidity readings. Bedload sediment is trapped in the weir ponds, and infill has been measured annually since 1962 using bathymetric surveys. Bedload was also measured from 1987 to 1997 in pit traps immediately upstream of the North Fork weir pond, and grain-size distributions of the transported material were measured.

Madej (2005) found that particulate organic matter (POM) accounted for ~19 to 24 percent of the annual suspended sediment load in the North and South Fork watersheds during 2002–2003, with the relative importance of POM decreasing with increasing discharge. Dahlgren (1998a) reported similar findings in the North Fork for the period 1991 to 1996.

Kopperdahl et al. (1971) reported concentrations of 83 to 155 ppm for total dissolved solids in the North Fork in 1968–1969, with concentrations that decreased with increased flow. Dahlgren (1998a) listed molar concentrations of the chemical

constituents in streamflow measured between 1991 and 1996, and calculated total dissolved loads and the percentage of dissolved organic matter. Sanderman (2007) measured dissolved organic carbon (DOC) in soil solutions, pipeflow, and stream water in a reference watershed during 2003–2005 and found that the pipeflow strongly influenced the characteristics of DOC in streamflow.

Many CCEW studies have focused on erosion processes. Major sources of sediment input include channel erosion (Reid et al. 2010), and landslides with volumes greater than 200 m³ (Reid and Keppeler 2012). Annually mapped streamside landslides are a lesser source. Plot erosion measurements showed minimal surface erosion in forested subwatersheds where much of the sediment is redeposited on hillslopes (Rice 1996). Ziemer (1992) found that sediment loads in soil pipes in a forested watershed were low.

Caspar Creek channels are strongly influenced by woody debris. Wood loading was measured in the North Fork in 1980 and 1986, and in both forks in 1994 and 1996. Wood was mapped and measured along the North and South Forks in 1998, and tagged pieces and new inputs have been remapped every 2 years since then (Hilton 2012). Russell (2009) described the species composition in riparian plots along the North and South Forks in 2001, and Reid and Hilton (1998) assessed blowdown in plots along the North Fork after a pair of major windstorms.

Information on stand characteristics is available from CAL FIRE. Continuous Forest Inventory plots have remeasured woody vegetation every 5 years since 1959, and Woodward (1986) and Rivas-Ederer (1998) inventoried both herbaceous and woody vegetation in plots across a gradient of disturbance ages.

Summer stream temperatures were monitored in the North and South Forks from 1963 to 1969, and monitoring resumed in the North Fork in 1988 and in the South Fork in 1998 (table 11.1). Under forested conditions, maximum dry-season stream temperature was 16.7 °C and seldom exceeded 15.6 °C, which was within an acceptable range for salmonid rearing. Nelson et al. (2007) found that air temperatures along a South Fork transect through the riparian zone increased upslope, with mean maximum weekly temperatures 4 to 5 °C higher at the upland sites than at the main-stem South Fork. Light levels were also measured at sites along the North and South Fork channels in 1965 to 1968, and again between 1989 and 1991 on the North Fork.

Dose-Response Studies

Dose-response studies for stream nutrients have not been conducted at CCEW.

Reference Watersheds

Three North Fork subwatersheds, ranging from 16 to 39 ha, serve as permanent references that are often referred to as “controls” in reports of CCEW research. Onsite human disturbance in the references is minimal, although residual effects of old-growth logging, 120 to 135 years ago, are reflected in the current characteristics of these second-growth stands, such as the presence of abandoned skid trails, and the incised stream channels. Although these references serve well for hydrologic and sediment research at the scale of the North and South Fork watersheds, they are not useful for studies of physical and biological conditions along the larger main-stem North and South Fork channels; such studies have usually used North Fork reaches adjacent to second-growth forest as reference reaches.

A reference subwatershed at the North Fork headwaters (Munn, abbreviated as MUN) has hosted multiple studies, in part because of the long-term subsurface hydrological monitoring carried out there. Soil moisture, pore pressure, and pipe-flow have been measured during various periods since 1987, and the site served as a primary source of reference data for a study of nutrient cycling (Dahlgren 1998a, 1998b) and for recent studies of N dynamics (Lennon and Houlton 2014, Mnich and Houlton 2016).

The reference watersheds are undergoing long-term changes as the second-growth forest matures, and future forest conditions will probably differ from those in the original old-growth stands. Wildfire recurred at 6- to 20-year intervals in the area before Euro-American settlement (Brown and Baxter 2003) and generated little tree mortality in the stands. Modern fire suppression has removed underburns from the ecosystem, and understory vegetation will change in response. In addition, two pathogens are becoming established in the region. Black-stain root disease (*Leptographium wagneri*) was identified for the first time at Jackson Demonstration State Forest in 1971, and recent high mortality rates for Douglas-fir and true fir, possibly associated with the pathogen, suggest that these tree species will become less common as the reference forest ages. Sudden Oak Death (*Phytophthora ramorum*) has also been found in Jackson Demonstration State Forest, and this disease may reduce tanoak (*Notholithocarpus densiflorus* (Hook. & Arn.) P.S. Manos, C.H. Cannon, & S.H. Oh) in the watersheds. In addition, future hydrologic regimes and forest characteristics in the area are likely to change in response to climate change.

Downstream characteristics may also shift through time. Recent woody debris is much smaller than relict old-growth wood and thus will decay and be displaced more quickly and will affect channel processes differently. In addition, declining populations of anadromous fish are reducing the inputs of marine-derived nutrients to streams and riparian zones (Moore et al. 2011).

Reference watersheds for the CCEW Experiment Three in the South Fork were selectively logged from 1971 to 1973, before implementation of modern forest practice rules, and contain networks of tractor skid trails and spur roads. These watersheds provide reference conditions for the forest that would be present after 1960s and 1970s logging if no further activities took place, and so are appropriate for evaluating the incremental effect of third-cycle logging taking place in the South Fork.

Cross-Site and Regional Studies

Nearly a third of the more than 225 publications, theses, and technical reports on CCEW research have focused on cross-site comparisons. CCEW results are often included in tabulations of sediment yields from forested and logged watersheds and in reviews of the hydrologic effects of logging. CCEW data are also often used to develop models or to test model results. For example, long-term data from CCEW were used by Breña Naranjo et al. (2011) to test a method for estimating evapotranspiration as forests regrow, and by Wang et al. (2010) to test flow routing models for watershed-scale applications of the Water Erosion Prediction Project model.

Other studies used CCEW data to represent conditions in temperate rain-dominated forests for comparisons over a range of climatic conditions. For example, Grant et al. (2008) drew upon these data in an evaluation of the effects of logging on peak flows, and Jones and Post (2004) for a comparison of hydrologic responses to tree harvesting in coniferous and hardwood forests. CCEW data were used by Jones et al. (2012) in an analysis of climate- and land use-related streamflow changes at 35 North American watersheds, and by Ponce-Campos et al. (2013) to evaluate the relation between water use efficiency and water availability among 29 sites in the United States and Australia. CCEW participates in ongoing research examining rates of wood decomposition as part of a continentwide study at 50 USFS and U.S. Department of Agricultural Research Service sites in the federal Ecotrends network (Peters et al. 2013). CCEW is among 18 USFS sites with climate monitoring stations that meet the International Co-operative Programme (ICP) Level II standards established by the ICP on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests 2010).

Much CCEW research has been carried out as an integral part of cross-site studies. An early sequence of papers examined biological (Burns 1971), physical (Burns 1970, 1972), and chemical (Kopperdahl et al. 1971) effects of road construction and logging across several coastal watersheds, including both forks of Caspar Creek. Other studies have compared DOC processing in forested CCEW soils with that in grassland soils (Sanderman and Amundson 2008); POM loads in managed

and old-growth redwood watersheds (Wilzbach et al. 2009); bed-material sizes and pool sedimentation across a range of sediment input rates (Lisle 1995, Lisle and Hilton 1999); and controls on N cycling and denitrification rates using N isotopes across a range of California ecosystems (Mnich and Houlton 2016).

CCEW was selected as a site for intensive monitoring of anadromous salmonids to aid design of a monitoring strategy for use throughout coastal California (Gallagher et al. 2010). Data from CCEW and several other intensively monitored watersheds are used to permit interpretation of sparser data collected at other coastal watersheds (Adams et al. 2011). Moore et al. (2011) combined data from CCEW and other monitoring sites to estimate rates of import and export of marine-derived P by anadromous fish.

Responses to Management and Natural Disturbances

Much CCEW research has focused on the effects of timber harvest operations on watershed processes and stream channel characteristics. Cafferata and Reid (2013) summarized CCEW results relevant to assessing management influences and described the ways that these results have been applied.

Kopperdahl et al. (1971) did not detect significant differences between nutrient concentrations in the North and South Forks after 1967 road construction. They noted that the major water quality effects were increased carbon dioxide (CO₂) and reduced dissolved oxygen (DO) from decay of instream logging debris and increased temperature from reduced shade. Management effects on nutrients were studied in more detail during the second harvesting treatment. Dahlgren (1998b) measured N content across the array of ecosystem components in reference and clearcut watersheds between 1991 and 1996. Losses attenuated quickly as a result of uptake by rapidly growing redwood stump sprouts. However, enough N was exported in the extracted logs that a deficit might occur after multiple logging cycles without adequate N fixation by blue blossom (*Ceanothus thyrsiflorus* Eschsch.), a shrub often controlled with herbicides. Moderate NO₃⁻ concentrations in stream water from clearcut watersheds decreased rapidly downstream and with time after logging, so little effect is expected farther downstream or with increasing time. Over a hypothetical 80-year clearcut rotation, the greatest logging-related change in N was from removal of logs, with lesser export in eroded sediment and leaching into streams.

Dahlgren (1998a) found that soil solution NO₃⁻ increased after logging, probably because of increased mineralization in warmer and moister soils and reduced uptake by vegetation. Nitrate concentrations in streams the first years after logging ranged between 0.6 and 3.1 mg/L (as NO₃⁻) during storms, with a maximum observed value of 4.3 mg/L. The USEPA (2017) drinking water standard is 45 mg/L

as NO_3^- or 10 mg/L as NO_3^- -N. Other soil solute concentrations declined after logging because of dilution. Phosphorus losses in streamflow were slightly higher after logging, but no significant change was found in soil P pools. Organic-rich sediment from the reference watersheds held a higher concentration of N than organic-poor sediment from clearcut watersheds, but sediment loads increased significantly after logging. Concentrations in suspended sediment of N (1.2 to 6.5 g/kg) and P (1.1 to 1.5 g/kg) were relatively high, indicating that increased erosion could lead to considerable nutrient loss following logging. Dahlgren (1998a) noted that N, P, and sulfur (S) are likely to be the most limiting nutrients for forest growth at the site. Gaseous losses via denitrification were found to be nearly an order of magnitude higher in a clearcut North Fork subwatershed several decades after logging than in a reference watershed (Mnich and Houlton 2016).

Keppeler et al. (1994) reported peak piezometric pressures that were 9 to 35 percent above prelogging levels at a clearcut site in the North Fork, and Ziemer (1992) found peak pipeflow was ~ 3.7 times greater than prior to harvest. These changes explain much of the difference that Dahlgren (1998a) found in soil and pipeflow nutrient concentrations between clearcut and forested sites. Storm runoff was found to increase after both South Fork tractor selection logging (Thomas 1990) and North Fork clearcutting (Lewis et al. 2001). Reid (2012) reevaluated South Fork data and found significant increases in peak flows across a range of discharges during the initial postlogging period; previous studies, which had grouped data from both the logging and postlogging period, had found significant changes only in small peaks. Wright et al. (1990) documented reductions in lag time for peak flows after South Fork logging. Ziemer (1998a) and Lewis et al. (2001) found increased peak flows across the range of storm sizes after North Fork clearcut logging. Results of the study were used to develop a peak flow prediction model that has been used to evaluate proposed logging plans in the region (Cafferata and Reid 2013). CCEW flow data were also used to test methods for estimating peak flows at ungaged sites (Cafferata et al. 2004, Cafferata and Reid 2013).

Annual water yields increased after both South Fork and North Fork logging (Keppeler 1998), while dry-season South Fork flows showed an initial increase followed by a lengthy reduction as regrowth progressed to below pretreatment levels 8 to 28 years after logging (Reid 2012). Reid and Lewis (2011) evaluated potential interactions between altered climate and logging as they may affect future dry-season flows at Caspar Creek. Reid and Lewis (2007, 2009) showed that reduced interception and transpiration are sufficient to explain observed changes in peak flows after North Fork logging. Later work evaluated the influence on dry-season flow of postlogging changes in interception and transpiration (Reid 2012).

Studies at CCEW have evaluated sediment inputs during roadbuilding (Krammes and Burns 1973), selection logging (Rice et al. 1979), and clearcut logging (Lewis et al. 2001). Other studies measured inputs from specific sources such as surface erosion (Barrett et al. 2012), gully erosion (Reid et al. 2010), and landslides (Cafferata and Spittler 1998, Reid and Keppeler 2012). Long-term monitoring showed renewed sediment increases from deterioration of old South Fork roads (Keppeler 2012), and sediment inputs are now being assessed from decommissioned roads. Early measurements of sediment from South Fork timber operations informed revisions to the California Forest Practice Rules, and CCEW data have been cited regularly in total maximum daily load (TMDL) documents, forest management plans, and other planning documents that address sediment concerns (Cafferata and Reid 2013).

Water temperature monitoring showed large increases in the South Fork during and after construction of a mainline road adjacent to the channel, with the maximum temperature at the downstream end of the study reach increasing from 13.9 to 21.1 °C (Burns 1972). Buffer strips prevented similar increases below a clearcut along a North Fork stream reach, with a daily maximum temperature of 16.1 °C (Cafferata 1990). Water temperatures recorded in the North Fork after logging were within the tolerable range for salmonids (Nakamoto 1998). Mean monthly dry-season stream temperatures did not exceed 14.6 °C. The South Fork channel continues to have relatively low levels of large wood after road construction, selection logging, and clearing of logging debris from the channel. Inputs of large wood along the North Fork increased after logging owing to blowdown in buffer zones exposed to increased wind at clearcut margins (Hilton 2012, Reid and Hilton 1998).

Graves and Burns (1970) suspected that high rates of juvenile salmonid emigration after South Fork road construction resulted from reduced habitat quality, but Nakamoto (1998) found no changes in salmonid populations attributable to North Fork logging. Bottorff and Knight (1996) documented increased postlogging macroinvertebrate density and diversity in the North Fork and concluded that changes in macroinvertebrates, algal growth, and leaf decay rates were consistent with some combination of increased temperatures, light, and nutrients after logging and not with an increase in sediment. The effects of specific influences could not be distinguished.

Reliability and Limitations of Findings

As with any long-term study, advances in monitoring technology both improve data quality and complicate comparisons between data collected during different periods. Long-term datasets thus need to be assessed during each application to assure that the attributes of interest are represented by an appropriately consistent record.

Studies that focused on understanding specific processes were most reliable for assessing causal mechanisms and produced results applicable to other sites with similar controlling factors. Because different processes respond to different controlling variables, areas over which results can be applied differ for different attributes. Cafferata and Reid (2013) described the areas of applicability for specific CCEW study results. Even within similar areas, transfer of quantitative results is most reliable if validation monitoring is done to test the application.

Studies that attempted to relate instream biological changes to specific causal mechanisms met with limited success owing to the variety of factors that influenced responses. Measurements were too few to identify specific causes for biological changes observed after South Fork road construction. During the second management experiment, Bottorff and Knight (1996) used a panel of response variables to try to identify causal mechanisms by comparing responses for different variables. However, logging was followed by a dry period, introducing an additional influence that complicated interpretation.

Results of long-term studies are sometimes dismissed as moot because land use practices and regulations change during the study period. However, if process mechanisms are understood, results can be applied under different management conditions by evaluating the influence of those new conditions on the causal mechanisms. In other cases, results are disregarded because experimental watersheds are often small. Studies of gradients in expression of changes over increasing scales (e.g., Lewis et al. 2001) allow likely effects to be estimated for larger areas. In any case, large watersheds are composed of smaller ones, so an understanding of changes in outputs from small watersheds can inform expectations of changes in larger basins.

Research Needs

The highest priority research need for the regulatory community related to N and P that might be filled by future studies at CCEW is a better understanding of how differences in riparian stand structure and composition affect seasonal light levels and nutrient availability that influence primary production and salmonid production.

Improved knowledge of these interactions between upland-riparian and instream nutrient dynamics would benefit regulatory agencies by providing a stronger scientific basis for establishing regulations for riparian zone management. Several aspects of this problem could be investigated by future research at CCEW. Long-term effects could be evaluated retrospectively by testing for differences in instream characteristics along South and North Fork Caspar Creek reaches that underwent different riparian disturbances in the past. Short-term

effects could be identified during future CCEW experiments by testing the outcomes of different riparian vegetation management treatments on stream properties such as light levels, above- and belowground organic material inputs, primary productivity, and DO in low- to mid-order stream reaches. Scale effects could be assessed by comparing outcomes of riparian treatments across a range of channel sizes. Research to address this need, however, is not part of CCEW Experiment Three that is currently underway and would require additional resources to implement.

Other research questions of interest to the regulatory community in the region, although of lower priority, that might also be addressed through future research at CCEW include the following:

- What long-term effects does forest management have on nutrient cycling, sediment production, forest productivity, and their interactions?
- What effects do reduced inputs of marine-derived N and P, from declining salmonid runs, have on stream and riparian biological processes?
- What effects do chronic turbidity durations and spatial distributions at a watershed scale have on anadromous salmonid growth and survival.
- What factors affect headwater stream temperatures?
- How effective are current California Forest Practice Rules for meeting Basin Plan water quality objectives?
- How effective are aquatic restoration projects for improving habitat conditions and food resources for salmonids?
- What are reference conditions for microbial pathogen levels in North Coast watersheds that support urban and agricultural uses?
- Would more efficient sediment budgeting methods improve assessments of the effects of planned land uses on water quality, nutrient loads, and stream sedimentation?
- How does climate change, including extreme weather events, affect nutrient cycling?

Potential Utility to Water Quality Regulatory Agencies

Results of CCEW studies are often used by California state and federal regulatory agencies as a basis for understanding the impacts of logging practices on water quality in the region (Cafferata and Reid 2013). Results from CCEW research regarding management-related effects of timber harvesting are expected to apply to other watersheds that support second-growth coast redwood in similar settings, and the basic understanding of watershed processes provided by these studies is even more widely applicable.

Baseline and postharvest information on hydrology, sediment, nutrients, and other characteristics in the watersheds have been used in TMDL documents for watersheds in similar settings. Results have also been used by regulatory agencies to evaluate potential impacts of timber harvesting plans and other projects that require agency approval. Additionally, Basin Plan amendments have been informed by CCEW results.

Monitoring methods developed at CCEW have reduced the cost and increased the efficiency and accuracy of suspended sediment monitoring (Lewis and Eads 2009), and these methods have been widely applied to water quality monitoring programs elsewhere. In addition, results of CCEW studies have contributed to the development of analytical tools and methods now used by regulatory agencies in the region (Cafferata and Reid 2013).

Key points:

- Stream water N outputs increased after clearcut logging but quickly decreased again owing to rapid revegetation by coast redwood stump sprouts.
- Increased runoff after logging explained much of the change observed in stream nutrient concentrations, and altered NO_3^- concentrations in streams also reflected changes in soil solutes in the A and AB horizons, the portion of the soil profile that contributes most to subsurface lateral flows.
- Nitrate fluxes after clearcutting were low compared to some eastern U.S. watersheds, and stream water concentrations did not exceed drinking water standards.
- Sediment inputs showed an increase 20 years after timber operations ceased as the network of roads and skid trails deteriorated; these delayed inputs likely affected instream nutrient processing.
- Associating aquatic biological responses with particular management-related changes is complicated by the suite of interactions among physical, chemical, and biological components that may be altered by management treatments.
- Regulatory agencies would benefit from a better understanding of the influences of riparian stands on instream nutrient and organic matter dynamics in order to design appropriate riparian management strategies.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Several regional nutrient issues do not involve N or P. There is growing interest in managing forest lands to enhance carbon (C) sequestration to mitigate global climate warming. In addition, S has been identified as a potential limiting nutrient in coast redwood forests. A third issue arises from the likely influx of air pollution from increased development in Asia. CCEW has few local air pollution sources upwind and may be ideally positioned to detect influxes of pollutants from Asian sources and to assess their effects on water quality.

Findings From Studies

Several studies relevant to C cycling have been carried out at CCEW. Sanderman and Amundson (2008) found that DOC leaches more deeply into soil and is retained longer under forest than in grassland, and they evaluated controls on soil CO₂ production and efflux (Sanderman and Amundsen 2010). Stream export of C from the watershed occurs both in solution and in the organic component of the suspended load, which Madej (2005) found to be appreciable at CCEW. Breakdown and transport of in-channel woody debris also results in C export, and measurements described by Hilton (2012) will allow evaluation of this component of C transport. Dahlgren (1998a) provided data on the distribution of C in biomass and soils in logged and forested subwatersheds.

Dahlgren (1998a) compared nutrient reservoirs with nutrient losses associated with logging and found that S, along with N and P, are the primary potential limiting nutrients in the CCEW forest. Sulfate (SO₄²⁻), like NO₃⁻, showed increased concentrations in stream water in the clearcut watershed. Unlike NO₃⁻, however, SO₄²⁻ concentrations decreased during periods of high flow, indicating its source may be in the lower soil horizons.

Dose-Response Studies

There have been no dose-response studies at the CCEW related to nutrients other than N and P.

Reference Watersheds

The description of CCEW reference watersheds presented above also pertains to studies regarding nutrients other than N and P. The reference watershed located at the North Fork headwaters has been a principal source of data owing to the long-term hydrologic datasets available for that site. Dahlgren (1998a, 1998b) measured

SO₄²⁻, calcium, magnesium, and potassium in this reference basin that were analogous to those already described for N and P. Sanderman (2007) carried out his study of DOC at the site.

Research Needs

The highest priority research need of the regulatory community, not directly related to N and P, that might be filled by future research at CCEW is more information on the effects of different silvicultural strategies on long-term rates of C sequestration in soils and on fluvial export of dissolved and particulate carbon. Results from such studies would provide regulatory agencies with a stronger scientific basis for considering C sequestration and greenhouse gas production in developing rules and guidelines for forest practices. Future studies at CCEW that might contribute to filling this gap would include developing more detailed C budgets for subbasins with different management treatments and comparing those results with similar budgets for unmanaged reference subbasins. At CCEW, large POM is trapped in the weir ponds, facilitating study of seasonal transport rates, and fine POM could be evaluated in samples taken routinely for sediment evaluation. Contrasts in riparian vegetation between the North and South Forks would allow for differences in organic C inputs from an alder-rich riparian zone to be compared with those from a coniferous riparian zone. Long-term silvicultural influences could be evaluated by comparing soil carbon storage across a range of silvicultural treatments in the watersheds ranging from past management treatments to those imposed in the next round of large-scale experiments. Monitoring emissions of greenhouse gasses, CO₂, methane and nitrogen oxide (N₂O), from streams and soils under different treatments could improve assessments of C fluxes. Research to address this need, however, is not part of the CCEW Experiment Three that is currently underway and would require additional resources to implement.

Other lower priority information gaps of interest to regulators that might be filled at CCEW include the following:

- How is POM transformed in stream channels, and how does it affect instream productivity, DO levels, and denitrification, including N₂O production?
- Will losses of S associated with forest management significantly limit future growth in coast redwood forests?
- Is the region receiving significant air pollution from Asia, and what are the implications of this pollution for water quality?

Potential Utility to Water Quality Regulatory Agencies

While CCEW clearcutting did not result in detectable short-term decreases in soil C (Dahlgren 1998b), C sequestration rates remain an important issue when considering contemporary impacts of forest management. Additionally, a study of nutrients removed in the biomass harvested indicated that S may be a critical nutrient when considering long-term forest productivity, meaning that regulatory agencies should be aware of potential future issues regarding forest S budgets. Information gained about the behavior of S in streams may lead to development of efficient protocols for monitoring S loss after logging.

Key points:

- It will be important to better understand sulfur cycling in these forests, as sulfur may be a limiting nutrient affected by forest management.
- Organic material is a significant portion of the sediment load at Caspar Creek.
- A high-priority research need for the regulatory community is improved understanding of effects of management on C cycling in these forests.

Overview and Synthesis

CCEW research has provided a scientific basis for understanding N and P fluxes in the watersheds and the effects of logging on those fluxes. Results indicate that stump sprouting of coast redwood quickly curtails increased nutrient export from logged sites. However, removal of timber over multiple logging cycles may lead to future nutrient deficits, and this could influence nutrient loads in streams. The effects on specific nutrient fluxes are strongly influenced by hydrologic changes caused by logging, both within soils and in streams. Understanding management-related changes in runoff and sediment input thus is key to predicting management-related changes in nutrient routing in this region.

Logging affected Caspar Creek flow primarily through reduced rainfall interception and transpiration. Long-term monitoring indicates that selection logging in the South Fork caused short-term increases in dry-season flows, but rapid regrowth curtailed those increases after nearly a decade and then led to a protracted period of summer flows that were lower than they were before cutting. Long-term monitoring showed renewed sediment inputs to streams 30 years after South Fork logging as the old road system deteriorated.

Aquatic biological responses to CCEW logging reflect a combination of altered flow, sediment loads, nutrient loads, light levels, woody debris inputs, organic material loads, and temperature. Not only do these factors individually affect biological

stream processes and aquatic ecosystems, but each affects the biological response to others. Untangling the web of interactions would require a combination of controlled experiments in both field and laboratory settings.

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Chapter 12: Ecoregion 7.1.8 Coast Range: Olympic Experimental State Forest, Washington

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Introduction

The Olympic Experimental State Forest (OESF) covers more than 110 000 ha on the western Olympic Peninsula in the state of Washington. The forest consists of state trust lands that are administered by Washington Department of Natural Resources (WADNR). The OESF is a working forest, managed to produce commercial timber sustainably and to provide ecological values, such as biodiversity and long-term site productivity. The OESF has an additional mandate, unlike other state trust lands in western Washington, to experiment with innovative land management practices and to put the research results into practice for continuous improvement of forest management. The long-term vision for the OESF is “of a commercial forest in which ecological health is maintained through innovative integration of forest production activities and conservation” (WADNR 1997).

The focus of the OESF is environmental monitoring and applied research to reduce key uncertainties in natural resource management. It also facilitates scientific projects at OESF by external researchers on a variety of environmental topics.

Because the OESF consists of numerous parcels of state-owned land interspersed with private, federal, and tribal lands (fig. 12.1), this synthesis also includes research and data from neighboring lands that are within the same drainage basins as the OESF parcels.

Site Description

The OESF is located on the western Olympic Peninsula of Washington, near the town of Forks (lat. 47° 57' 37" N, long. 124° 23' 30" W) (fig. 12.1). The forest encompasses all state trust lands managed by WADNR within a polygon defined by Washington Department of Ecology's (WADOE) water resource inventory area No. 20 (Sol Duc/Hoh) and portions of areas No. 19 (Lyle/Hoko) and No. 21 (Queets/Quinault). Elevations range from 0 m near the Pacific Ocean to 1155 m at the upland border with the Olympic National Park (ONP).

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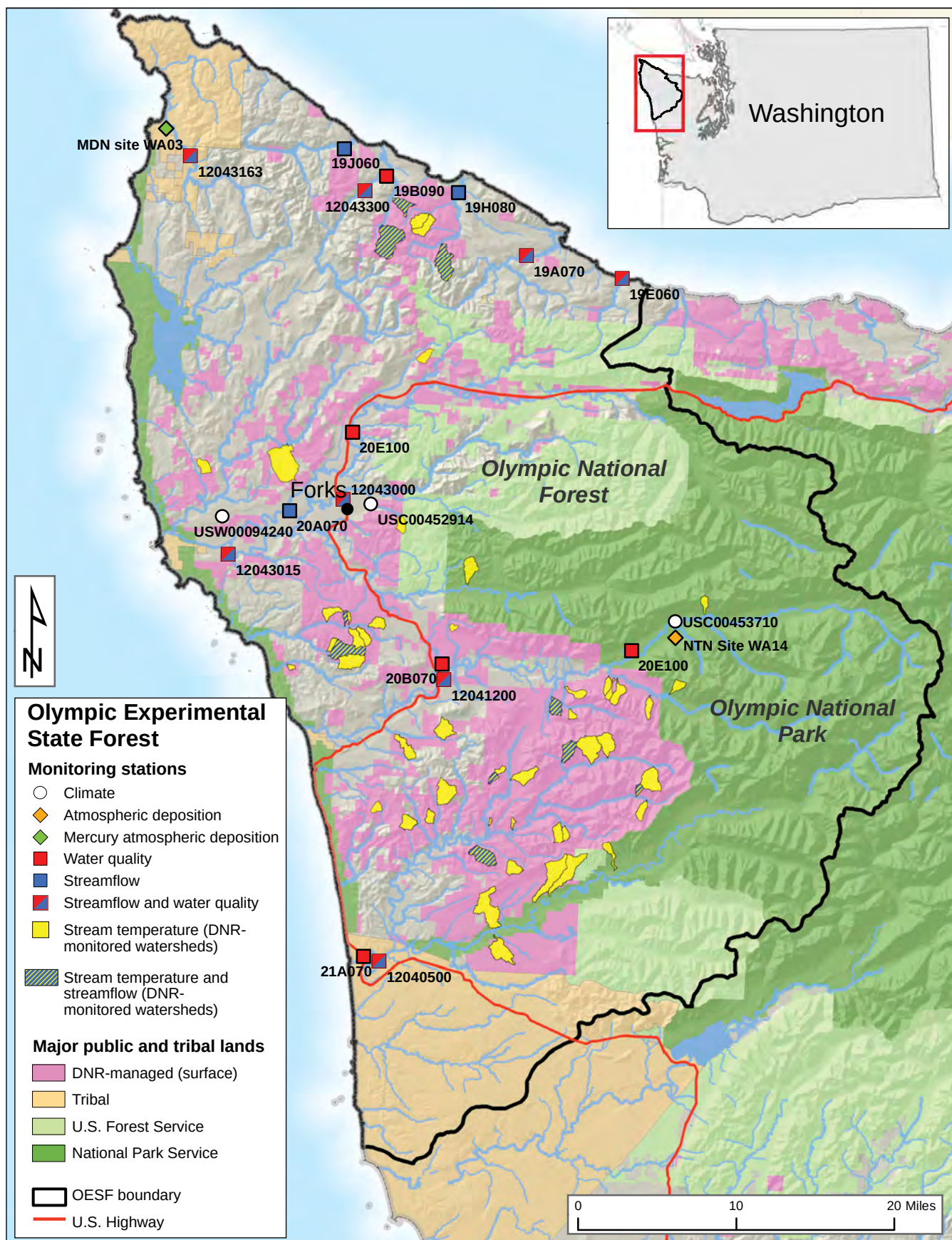


Figure 12.1—The Olympic Experimental State Forest (OESF) consists of all Washington Department of Natural Resources (DNR)-managed lands within the OESF boundary. Monitoring locations of mainstem rivers and of atmospheric deposition are identified by station ID. Small watersheds, monitored by Washington State DNR for stream discharge and water temperature, are color-coded. NTN = National Trends Network. MDN = Mercury Deposition Network.

Most soil parent material is uplifted marine sedimentary and basaltic rocks with surficial continental and alpine glacial deposits. The area is characterized by a maritime climate with annual precipitation of 200 to 457 cm, most falling as rain from October through May. Snowfall is rare in lower elevations, with snowpack usually only above ~600 m. Streamflows are largely rain dominated with pronounced seasonal low flows during drier summer months. Strong winds from the Pacific Ocean, floods, and debris flows are the major natural disturbance forces.

Major coastal river systems run through the OESF, including the Bogachiel, Clearwater, Hoh, Hoko, Pysht, Queets, and Quillayute Rivers. Steep erodible terrain and heavy annual precipitation produce high stream densities of ~3.6 km/km² and more than 4000 km of mapped streams. Most streams have high gradients and channel deposits of rocks and large wood mainly derived from unstable channel banks and debris flows that originate in steep tributary basins. The combination of high rainfall and soil layers that restrict water movement produces numerous wetlands.

The Sitka spruce (*Picea sitchensis* (Bong.) Carriere) vegetation zone dominates along the coast (Franklin and Dyrness 1973). Inland, the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) zone comprises a majority of the forest. In this zone, western red cedar (*Thuja plicata* Donn ex D. Don) occurs in the areas with wetter soils. Major seral components of vegetation are Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in all zones and red alder (*Alnus rubra* (Bong.) at lower elevations. The Pacific silver fir (*Abies amabilis* (Douglas ex Loudon) Douglas ex Forbes) zone, at higher elevation, comprises a minor portion of the OESF. Abundant moisture and a long growing season result in high tree-growth rates. Old-growth forests that once dominated the landscape still exist on about 11 percent of OESF. Around 50 percent of the OESF consists of younger stands resulting from extensive logging since the 1970s and 1980s (WADNR 2016b).

Streams and riparian areas in the OESF provide habitat for a diversity of fish, including at least nine resident or anadromous salmonid species: sockeye salmon (*Oncorhynchus nerka* Walbaum), pink salmon (*O. gorbuscha* Walbaum), chum salmon (*O. keta* Walbaum), Chinook salmon (*O. tshawytscha* Walbaum), coho salmon (*O. kisutch* Walbaum), steelhead (*O. mykiss* Walbaum), cutthroat trout (*O. clarkii* Richardson), bull trout (*Salvelinus confluentus* (Suckley)), and mountain whitefish (*Prosopium williamsoni* (Girard)). Seventeen other fish species, including lampreys, minnows, suckers, and sculpins, are known to occur in the OESF. The western Olympic Peninsula has more robust salmonid populations than other areas of the northwest Pacific coast, south of Canada (Huntington et al. 1996, NPCLE 2015). Bull trout and the Lake Ozette sockeye (an evolutionarily significant unit of *O. nerka*) are the only local fish species listed as threatened under the Endangered Species Act (ESA; 16 U.S.C. 1531-1544, 1538-1540).

A mandate from the state legislature directs WADNR, as a fiduciary of these trust lands, to actively manage the OESF to provide revenue in perpetuity for specific trust beneficiaries such as public schools and universities. Most revenue comes from timber harvest. On average, 600 ha, or 0.55 percent of the land area, were harvested annually in the OESF between 1999 and 2014. OESF is also managed to provide ecosystem values, including conservation of habitat for federally protected species, which is guided by a habitat conservation plan (HCP) (WADNR 1997). Details of OESF biophysical conditions and management are contained in the OESF forest land plan (WADNR 2016b).

Research History

The OESF was designated by WADNR in 1992 to learn how to integrate timber harvest and habitat conservation across the landscape and to implement new knowledge, such as innovative silvicultural techniques, into land management decisions. Under the HCP, the OESF research and monitoring program focused on addressing three main conservation strategies to restore and maintain habitat for salmon, northern spotted owls (*Strix occidentalis caurina*), and marbled murrelets (*Brachyramphus marmoratus*) (WADNR 1997). The majority of research and monitoring studies in the OESF, conducted or funded by WADNR, have focused on evaluating the habitat and species response to management typically practiced on state lands, specifically timber harvest and associated road management activities. Research on fundamental ecological processes has been primarily performed by scientists from cooperating agencies and universities.

Studies within the OESF have included silvicultural research (Ahrens and Bluhm 2016, Himes et al. 2013), species and habitat response to forest management (Cederholm and Reid 1987, Horton 2008, Raphael et al. 2008), long-term effects of forest management on soil and vegetation productivity (Homann et al. 2008), hillslope erosion (Reneau et al. 1989), regrowth response of vegetation to natural disturbances (Huff 1995), and long-term monitoring of aquatic and riparian conditions across the OESF (Minkova et al. 2012).

An important element of the OESF mission is to demonstrate an adaptive management process for integrating intentional learning into WADNR's decisionmaking on management of state lands. The process starts with identifying and prioritizing knowledge gaps that affect management of natural resources, followed by developing and implementing research and monitoring projects to address these needs, and finally using the scientific results to inform adjustments of future management activities and strategies (WADNR 2016b).

Several government agencies have conducted long-term environmental monitoring on lands adjacent to the OESF. Many of these environmental monitoring data are

relevant to research projects on the OESF. The U.S. Geological Survey (USGS) and WADOE have monitored streamflow on main-stem rivers adjacent to the OESF since 1930, and intermittently measured water quality since 1960. The National Oceanic and Atmospheric Administration (NOAA) has monitored climate at Forks, Washington, since 1907. The National Park Service (NPS) has monitored atmospheric deposition chemistry at the ONP Hoh Ranger Station since 1980. Washington Department of Fish and Wildlife (WDFW) and tribal fisheries agencies have monitored adult salmon returns through redd surveys in main-stem rivers since 1973. In 2009, the OESF joined the experimental forests and ranges (EFR) network, under an agreement between WADNR and the U.S. Forest Service (USFS) Pacific Northwest Research Station that encouraged collaboration between the OESF and USFS scientists.

Availability of publications and data—

A bibliography of environmental research and monitoring carried out on the western side of the Olympic Peninsula through 2008, including the OESF, is available at the WADNR website (Teply and Phifer 2008). Descriptions and documentation of ongoing and recently completed research and monitoring projects are available at the WADNR website (WADNR 2017). Various datasets from ongoing and past projects as well as annotated bibliographies may be obtained by contacting the OESF research and monitoring manager.

Locations and URLs of long-term monitoring sites on the OESF and its vicinity are in table 12.1 and figure 12.1. Daily climate and streamflow data from the USGS- and NOAA-operated stations near the OESF, formatted for ready comparison with other EFR sites, may be downloaded at the Long Term Ecosystem Research (LTER) Network data portal (LTER Network 2011). Stream temperature data collected by WADNR in 50 monitoring watersheds within the OESF and 4 watersheds within the adjacent ONP (fig. 12.1) are available at the NorWeST Regional Stream Temperature Database (USDA FS 2017).

Biological Responses to Stream Nutrients N and P

Issues of Concern

The western Olympic Peninsula is primarily a forested landscape with a relatively sparse human population and few sources of pollutants typically associated with urban, suburban, industrial, or agricultural areas (Klinger et al. 2008). Streams within the OESF are generally oligotrophic and mostly nitrogen (N) limited (Fevold 1998). Water quality concerns about N and phosphorus (P) primarily arise from forest management activities, such as timber harvest and road use, maintenance, and construction; reduced numbers of adult salmonid returns; and the potential for increased air pollution originating from eastern Asia.

Table 12.1—Long-term environmental monitoring stations on and near the Olympic Experimental State Forest^a

Monitoring type	Station ID	Station name	Operated by	Period of available data	Reference
Climate	USW00094240	Quillayute State Airport	NOAA	1966–present	NOAA 2017a
Climate	USC00452914	Forks 1 E	NOAA	1907–present	NOAA 2017b
Climate	USC00453710	Hoh Ranger Station	NOAA	2004–present	NOAA 2017c
Streamflow and water quality	12043300	Hoko River near Sekiu, WA	USDI	1989–present	USDI GS 2017a
Streamflow and water quality	12043163	Tsoo-Yess River BLW Miller Creek near Ozette, WA	USDI	2010–present	USDI GS 2017b
Streamflow and water quality	12043015	Bogachiel River near La Push, WA	USDI	2017–present	USDI GS 2017c
Streamflow and water quality	12043000	Calawah River near Forks, WA	USDI	1989–present	USGS 2017d
Streamflow and water quality	12041200	Hoh River at U.S. Highway 101 near Forks, WA	USDI	1989–present	USDI GS 2017e
Streamflow and water quality	12040500	Queets River near Clearwater, WA	USDI	1988–present	USDI GS 2017f
Water quality	20B070	Hoh River at Department of Natural Resources Campground	WA DOE	1960–present	WADOE 2017h
Water quality	21A070	Queets River at Queets	WA DOE	1960–1972, 1994	WADOE 2017i
Water quality	19B090	Hoko River near Sekiu	WA DOE	1973 and 1974	WADOE 2017j
Water quality	20E100	Twin Creek and Upper Hoh Road Brook	WA DOE	2011–2015	WADOE 2017k
Water quality	20E100	Sol Duc River near Forks	WA DOE	1972–1974 and 1994	WADOE 2017l
Streamflow	20A070	Sol Duc River near Quillayute	WA DOE	2005–2012, 2013–present	WADOE 2017b
Streamflow	19J060	Sekiu River above Carpenter Creek	WA DOE	2006–2010, 2011–present	WADOE 2017k
Streamflow	19H080	Clallam River near Clallam Bay	WA DOE	2005 – present	WADOE 2017d
Streamflow and water quality	19E060	Deep Creek near Mouth	WA DOE	2005–2015	WADOE 2017e
Streamflow and water quality	19A070	Pysht River near Pysht	WA DOE	1972–1974	WADOE 2017e
Atmospheric deposition	NTN Site WA14	Hoh Ranger Station	NADP	1980–present	NADP 2019a
Mercury atmospheric deposition	WA03	Makah National Fish Hatchery	NADP	2007–present	NADP 2019b

NOAA = National Oceanic and Air Administration, USDI = U.S. Department of the Interior, USGS = U.S. Geological Survey, WA DOE = Washington Department of Ecology, NADP = National Atmospheric Deposition Program, NTN = National Trends Network.

^a See figure 12.1 for general locations.

Forest management activities have been found to increase N in streams (Gravelle et al. 2009, McIntyre et al. 2017, Richardson and Béraud 2014). Changes in composition and age of riparian vegetation as a result of forest management practices, particularly N fixation associated with alder, can change N and P concentrations in riparian ecosystems (Boggs and Weaver 1994). Additionally, forest roads can be a source of fine sediments and both N and P within a watershed (Forsyth et al. 2006). Improved forest practices, such as the use of riparian buffers and upgrades and decommissioning of forest roads, have been implemented by WADNR and other land managers to reduce the effects of management activities on inputs of sediment and N and P to streams. While increases in N and P from forest management activities might be beneficial to streams with lower productivity, uncertainties remain around the timing and duration of these nutrient pulses as well as the responses of salmonids and other biota.

Although Olympic Peninsula salmon populations are considered relatively healthy compared to salmon populations in other areas of the continental United States, they have been significantly reduced from historical conditions (Cederholm et al. 1989, NPCLE 2015, PFMC 2001). Salmon are regionally important as a commercial and recreational fishery and as a cultural heritage of native peoples. When anadromous salmonids return to spawn and die, they transport marine N and P to the streams. These fish-transported nutrients promote biological productivity in riparian and stream ecosystems (Cederholm et al. 1989, Gresh et al. 2000, Helfield and Naiman 2001). The long-term decline of adult salmon may also alter food web complexity, including carnivore abundance in coastal streams and their watersheds. Current resident and juvenile anadromous salmonid populations within the OESF may be experiencing lower productivity owing to reduced marine-derived N and P in streams as a result of decreased adult returns.

The quality of salmon spawning and rearing habitat depends on an array of critical features, including water temperature, the composition and age of riparian vegetation, instream wood, suitable spawning gravels, and the number and size of pools (Hicks et al. 1991). Impacts of past forest management practices on these critical habitat features have been identified as a factor contributing to the long-term declines observed in northwestern salmon stocks (Cederholm and Reid 1987, Hartman et al. 1996, Lawson 1993, Tschaplinski 2000).

Rapid economic and industrial growth in upwind, eastern Asia might increase the deposition of pollutants to the Pacific Northwest in the future (Sheibley et al. 2014). Potential effects of increased deposition on streams are complex. For example, in the short term, increased atmospheric inputs of nutrients, such as N,

might increase stream productivity (Volk et al. 2008), while over the longer term, this pollutant might acidify streams and negatively affect fish (Camargo and Alonso 2006). Other potential pollutants in deposition, such as toxic heavy metals and pesticides might accumulate in stream food chains with undesirable consequences (Kelly et al. 2008).

Findings From Studies

Regional monitoring—

Data on N and P in precipitation and stream water are available from several sampling stations maintained by various state and federal agencies (table 12.1; fig. 12.1). The WADOE has maintained a water quality monitoring site in the Hoh River on the OESF since 1960, with monthly measurements from 1994 to 2015 of ammonium (NH_4^+), nitrate (NO_3^-), total persulfate N and P, and nine other indicators of water quality. In addition, WADOE has collected intermittent water quality data from sites in the Hoko (1973 and 1974) and Queets (1960–1970, 1972, and 1994) Rivers.

Within the Hoh River drainage, stream water and precipitation chemistry, including N and P, were collected during 1984–2004 from West Twin Creek watershed in ONP and during 1999–2004 from Linder Creek watershed within the OESF (Stottlemeyer et al. 2002). Stream water quality on local mainstem rivers has been monitored intermittently by USGS, including measurements of N and P, suspended sediment and dissolved oxygen (DO) in the Hoh River (1960–1980), the Calawah River in the mid-1970s, and the Queets River (1977–1993). A 1978 water quality assessment, including N and P, of the Hoh River watershed sampled 13 sites in the main-stem Hoh and 12 tributaries (Lum 1986). The ONP has participated in the National Atmospheric Disposition Program (NADP) monitoring atmospheric deposition of NH_4^+ , NO_3^- , and inorganic N at Hoh Ranger Station since 1980.

Studies of N and P—

Studies of West Twin Creek, at the ONP and Linder Creek at the OESF, monitored precipitation, throughfall, stemflow, soil solution, stream chemistry, hydrology, vegetation, annual litter fall, and litter decomposition (Edmonds et al. 1998). Analyses of trends found significant increases in stream water NH_4^+ and NO_3^- over the period 1994–2001, but there was no significant long-term trend in phosphate (PO_4^{3-}). Possible sources of increased NO_3^- were speculated to be air pollution originating from Asia or unknown oceanic sources (Stottlemeyer et al. 2002). Stream water NO_3^- concentration exhibited seasonal patterns with peaks in the fall and early winter probably from leaching of NO_3^- during the rainy season that accumulated in soils and sediments during the dry season (Edmonds and Blew 1997).

Volk (2004) compared streams dominated by N_2 -fixing red alder in the Clearwater watershed with streams dominated by old-growth conifer forests in the Hoh watershed. Leaf litter, leaf detritus, and periphyton had higher concentrations of N and P in alder-dominated streams than in conifer-dominated streams. Algae and invertebrate communities in alder-dominated streams had higher production (biomass) and food quality, as measured by essential fatty acid and elemental nutrient contents. Higher production of invertebrate biomass in alder compared to conifer streams was also transferred downstream via drift and to adjacent terrestrial environments via insect emergence.

Volk and Kiffney (2012) conducted another study in the headwater streams of the Hoh and Clearwater watersheds to determine whether leaf litter inputs from alder influence the relative abundance of fatty acids of instream organisms. Primary producers are the only source of these fatty acids for higher trophic levels. Although the concentrations of N and P were significantly higher in fresh alder foliage than in conifer foliage, the results showed little evidence that riparian vegetation type influenced fatty acids and elemental nutrients in periphyton, invertebrates, or trout.

Jackrel and Wootton (2014) examined the effects of nutrient content and concentration in alder leaf litter on its decomposition in streams in the South Fork of the Pysht River drainages. Litter quality was manipulated by producing leaves high in P by fertilizing alder trees with triple super phosphate (P_2O_5) and leaves with a higher carbon (C)-to-N ratio were produced by punching holes in leaves of unfertilized alder trees to simulate herbivory. Leaf packs containing control, fertilized, or simulated-herbivory leaves were placed in streams. Fertilized leaves retained slightly more of their starting P content over time than control leaves, but there was no significant difference in P levels between treatment groups. Compared to the unmanipulated control, the rate of consumption of leaf litter by aquatic decomposers was suppressed by the simulated herbivory treatment, which increased the leaf C:N ratio, but was not affected by P fertilization.

Dose-Response Studies

A dose-response study by Volk et al. (2008) compared nutrient limitations in streams with riparian areas dominated by alder or by conifer species. The three conifer-dominated streams were relatively pristine and located in the ONP. The three alder sites were logged approximately 30 years prior to the study and were located on the OESF. Porous glass frits with N or P infused agar mediums (0.05 M, 0.1 M, and 0.5 M) were placed in high sunlit runs within 100-m sections of streams above fish barriers. Frits were removed from the stream after 14 days and analyzed

for chlorophyll *a* (chl *a*). Concentrations of chl *a* in alder streams were double the concentrations found in conifer streams after treatment. In both alder and conifer streams, there was no significant differences in chl *a* response between nutrients added (N and P) or nutrient concentrations. Because both alder and conifer streams responded to N and P additions, the authors concluded that both nutrients were limiting production in both of these stream types.

Other Factors Relevant to Stream Nutrients N and P

The role of hydrologic processes—

Studies conducted by Bechtold et al. (2003) in the Queets River watersheds demonstrated the dominance of hydrologic processes in controlling N flux in aquatic ecosystems on the western Olympic Peninsula and specifically the seasonal movement of NO_3^- from riparian soils to aquatic areas. These data support a two-phase conceptual model of N leaching. During dry summer periods of low flow, the primary N source entering streams was water with low NO_3^- and insignificant dissolved organic carbon (DOC) concentrations, draining from unsaturated upland soils. During peak streamflows, typically associated with winter conditions and frequent precipitation, saturated soils bordering stream channels yielded water with high concentrations of NO_3^- and DOC that became the main source of solutes to streams. They hypothesized that, although the highest NO_3^- fluxes and surface water concentrations occurred during peak flows, the NO_3^- entering streams during low flows probably exerted a greater influence on stream productivity. During low flows, NO_3^- remained in the stream reach long enough to be available for uptake by aquatic biota, whereas during peak flows, NO_3^- was too rapidly flushed from the system to be absorbed by biota.

Effects of reduced salmonid populations—

When anadromous salmonids return to spawn, they make substantial contributions of nutrients to the stream, terrestrial vegetation, and to various species of wildlife. Several studies on marine-derived nutrients on the western Olympic Peninsula have included sites within the OESF. These studies have quantified marine-derived N in streams (Bilby et al. 2001) and examined the levels of retention and utilization of nutrients from salmon carcasses (Cederholm et al. 1989, 1999). These studies raised concerns that decreases in nutrients, as a result of salmonid population declines, may hamper salmon recovery efforts.

The role of physical habitat attributes—

In 2012, WADNR initiated an OESF-wide watershed monitoring project to determine the long-term status and trends in aquatic habitat within the OESF. The objective is to evaluate the changes in habitat attributes as WADNR implements planned management activities in the monitored watersheds. The monitoring information will be used to test WADNR projections for habitat recovery (WADNR 2016a), to conduct monitoring and experiments on salmonid response to managed landscapes, and to implement smaller scale aquatic ecology research. Fifty study watersheds, with an average size of 122 ha, were selected for monitoring in the OESF by using a random, stratified design from an inventory of all catchments within the OESF that are drained by the smallest fish-bearing streams ($n = 848$). WADNR has harvested timber on most of the selected OESF study watersheds in the past. Future timber management is planned in many of the monitored watersheds in accordance with the OESF forest land plan (WADNR 2016b).

Twelve reference basins, which are relatively pristine watersheds with minimum human disturbance, are also monitored as part of this project. Four of these reference basins are located on adjacent ONP lands under an agreement with the NPS, six are on ONF lands under an agreement with the USFS, and two are on state lands within the OESF.

The project systematically monitors indicators of aquatic and riparian habitat at the outlet of each study watershed, where disturbances within the basin are expected to be cumulatively expressed. The monitored habitat parameters are as follows: stream temperature, instream large wood, stream shade, coarse channel substrate, stream habitat units, classification of valleys and channel reaches, stream morphology, riparian microclimate, and riparian vegetation. In 2013, continuous monitoring of stream discharge and riparian microclimate (air temperature and humidity) was initiated on a subset of 10 of the study watersheds (Minkova and Vorwerk 2014). Monitoring of water chemistry (total N, total C, NH_4^+ , nitrite (NO_2^-), NO_3^- , PO_4^{3-} , and DOC) and salmonid populations were added in a portion of the watersheds in 2016. The study watersheds are also monitored remotely with LiDAR and aerial photography and with operational records for ongoing and past disturbances such as windthrow, landslides, timber harvest, and road management. The first round of field sampling of habitat characteristics was completed on all 54 watersheds in 2015 and will be repeated every 3 to 5 years. The 2015 results show that most of the monitored streams are well-shaded, because of dense second-growth riparian forest; have cool summer stream temperatures that are generally below regulatory temperature thresholds for salmonids; and have relatively low volumes of instream large wood that is beginning to accumulate (Minkova and Devine 2016).

Reference Watersheds

The purpose of the reference basins is to provide the status and trends in aquatic and riparian habitat conditions in relatively pristine, unmanaged watersheds and to account for the natural background variation that might mask the OESF basins' response to management. All reference watersheds are in the vicinity of the OESF managed study watersheds; similar to them in study basin area, elevation range and other physiographic characteristics; and are dominated by conifer forests that have never been harvested.

Twelve reference study watersheds are being monitored within the OESF and on nearby lands within the ONP and ONF. The two reference watersheds on state lands in the OESF are within the Hoh and the Bogachiel River basins. The four reference watersheds established in the ONP are within the Hoh, the Queets, and the Bogachiel River drainages (shown in fig. 12.1) (Minkova et al. 2012). The six reference watersheds established within the ONF are all within the Bogachiel River basin. The eight reference watersheds located on the OESF and ONF lands have been established since 2017 and are not shown in figure 12.1.

The ONP reference watersheds have been formally protected from onsite human disturbance since the ONP was established in 1938, and even before that, probably had little human disturbance owing to their remote mountainous locations. Streams in these ONP reference watersheds have been monitored since 2012 for the same stream physical habitat attributes that were monitored on the managed study basins within the OESF. Long-term monitoring of fish populations, stream water inorganic N chemistry, and riparian vegetation were added in 2016.

The ONF reference watersheds have been formally protected from onsite human disturbance since the adoption of the Northwest Forest Plan in 1994. Streams, fish populations, and riparian vegetation have been monitored in the reference watersheds on ONF and OESF lands since 2018, following the same protocols as the reference basins within the ONP.

Cross-Site and Regional Studies

A number of cross-site studies have included observations made in the OESF or on adjoining ownerships that have been compared with other sites in the region or nation. These studies provide perspective about how streams in the OESF compare to streams in a larger geographic or ecologic context. Bilby et al. (2001) included six streams within basins that drain the OESF in a sample of 26 sites across western Washington to examine the relationship between the abundance of spawning coho salmon and the stable isotope ratio ^{14}N : ^{15}N of young coho salmon parr. The study examined whether a saturation level for salmon-derived N could be

identified. It found a relationship between the degree of enrichment with ^{15}N and abundance of spawning salmon and concluded that streams in western Washington were capable of incorporating substantially more marine-derived nutrients than they have received over the past several decades. The authors suggested a method for setting escapement goals that considers the importance of spawning anadromous salmon for productivity of the habitats in which subsequent generations hatch and rear.

A study on West Twin Creek conducted in the upper Hoh River watershed on the ONP between 1984 and 2004 was used in a nationwide synthesis of ecosystem monitoring sites in five national parks across the United States (Stottlemyer et al. 2002). The ONP had the second lowest input of atmospheric N among the five national parks. The study found no trend in ONP stream NO_3^- from 1985 to 1993, but found an increasing trend from 1994 to 2001 and attributed this trend to pollution from Asia or to oceanic sources.

Blinn (2015) correlated stream environment physiochemical conditions with assemblages of diatoms in 165 aquatic systems in Washington, including the Olympic Peninsula, to assess diatoms as environmental indicators of land use and elevation. Diatom species richness showed significant positive correlations with stream water total N, total P, pH, and specific conductance, channel embeddedness, and water temperature, and it showed a negative correlation with canopy cover.

Streams from the OESF were included in a biological assessment of small streams of the Washington Coast Range and inland Yakima Basin (Merritt et al. 1999). Macroinvertebrate and fish assemblages, physical habitat, and water chemistry were used as indicators. Stream water chemistry was measured, including N, P, suspended solids, temperature, and DO. Streams in the Coast Range had relatively low levels of nutrients, alkalinity, and conductivity; poor physical habitat conditions; and impaired biological integrity. The study reported average levels for nitrate + nitrite (0.11 mg/L), NH_4^+ (0.02 mg/L), total P (0.02 mg/L), and total persulfate N (0.23 mg/L) for all of the 47 Coast Range sites, of which 17 were within the OESF.

Moore et al. (2009) included the ONP in a cross-site analysis to determine the effects of climate change on glacial retreat across the western United States. The findings imply that, similar to glacier-fed streams in other western mountains, future glacier retreat in the Olympic Mountains will likely result in higher stream temperatures, possibly transient increases in suspended sediment, and changes in water chemistry in glacier-fed main-stem rivers that flow through the OESF, such as the Hoh, Queets, and Quinault Rivers. None of the headwater study basins currently monitored in the OESF, the ONF, and the ONP are glacier fed, so glacier

retreat is unlikely to affect their waters directly, although anadromous fish migrations to and from the OESF, ONF, and the ONP study basins might be altered if conditions change in main-stem rivers through which these fish migrate..

Jones et al. (2012) included the OESF in a cross-site synthesis of climate effects, specifically air temperature and precipitation, on streamflow in a collection of 35 headwater basins at EFR and LTER sites across the United States. The OESF was among the sites with the highest annual precipitation and runoff, and water yield per unit land area, and the highest ratio of runoff to precipitation in this nationwide collection of intensively studied watersheds. The authors suggested that declining streamflow at several sites, including declines during the spring season at the OESF, may be the result of increased evapotranspiration in response to warmer temperatures.

Long-term atmospheric deposition data, collected by the NPS at its Hoh Ranger Station, in proximity to the OESF, have been used in nationwide analyses of atmospheric deposition by the NADP (NADP 2019a). These analyses showed that, in the vicinity of the OESF, atmospheric deposition of nutrients of nonmarine origin is very low, as is typical of coastal areas downwind of the Pacific Ocean and remote from local sources of air pollution. However, other studies in the ONP (Edmonds et al. 1998, Stottlemeyer et al. 2002) and in nearby British Columbia (Wilkening et al. 2000) have documented increases in stream nitrates and sulfates and speculated that these increases might be from atmospheric deposition of airborne pollutants from Asia.

Federal land management agencies participate in the Aquatic and Riparian Effectiveness Monitoring Program (AREMP), which evaluates whether the Northwest Forest Plan's aquatic conservation strategy is achieving its goal of maintaining and restoring salmon habitat on federal lands in western Washington and Oregon and northwestern California (Reeves et al. 2004). This program was designed to systematically assess the long-term status and trends in salmonid stream habitat over ~10 million ha, a geographic scope and scale that was unprecedented. Five of the fifty watersheds that are monitored by this program are located on the ONF streams in the Queets, Quinalt, Solduc, and Calawah watersheds in which the OESF is located. The long-term status and trends monitoring of riparian and aquatic habitat at OESF adopted study objectives and design and field methods that are similar to those used by AREMP (Minkova et al. 2012). AREMP analyses of the Olympic Peninsula basins on federal lands for 1993–2012 indicated moderate, broad-scale improvements in aquatic habitat quality and particularly channel substrate, water temperature, and macroinvertebrate diversity. This trend was attributed to regrowth of forest vegetation and road decommissioning (Miller

2017). It is possible that streams within WADNR lands of the OESF are showing a similar improvement, but because land management differs between the OESF and ONF, monitoring data currently being collected on stream habitat conditions in the OESF will be need to be analyzed to test whether conditions in OESF streams are following trends observed on federal lands.

Responses to Management and Natural Disturbances

On the western Olympic Peninsula, changes of stream temperature have mainly been studied in relation to harvest activities. Pollock et al. (2009) studied summer stream temperature at 40 locations in the Hoh and Clearwater drainages within the OESF in 2004 to relate stream temperature to basin harvest activities. They found that temperature was significantly higher in harvested basins compared with unharvested basins and that past harvest was still having an effect on temperature, even with the use of riparian buffers. Similarly, Hatten and Conrad (1995) found that temperatures in 28 streams within and around the OESF were significantly higher in managed forests than in unmanaged forests.

Murray et al. (2000) compared two partially harvested watersheds in the OESF with the Twin Creek reference site on the ONP for evidence of changes in stream chemistry, temperature, and turbidity. Partial harvesting (harvesting between 7 and 33 percent of the land area) had a minimal effect on these indicators 11 to 15 years after harvesting. Stream temperatures were more seasonally variable in the harvested streams compared to an unharvested old-growth site, with summertime maximums elevated by 3.5 °C. Higher and more prolonged NO_3^- levels were also observed in the disturbed watershed streams 11 to 15 years postharvest, a difference that may be attributed to N-fixation associated with red alder growing in harvested riparian areas. There appeared, however, to be little long-term influence of harvesting on stream pH, alkalinity, electrical conductivity, and total N and P concentrations. Total N and P concentrations were not different among streams and were generally low, with a range of 0.0 to 0.62 mg/L for N and 0.0 to 0.72 mg/L for P.

A replicated, large-scale experiment manipulated riparian vegetation along the South Fork Pysht River in 1994 (Wootton 2012) to investigate how reducing riparian vegetation cover would affect salmon rearing habitat. Experimental reduction of stream canopy cover did not affect water temperature, nutrient limitation, or other physical habitat characteristics. Nutrients NO_3^- , NO_2^- , NH_4^+ , PO_4^{3-} , and DOC, and silicates were also not changed significantly by riparian treatments. In contrast, stream biological components responded strongly. Although reductions of stream canopy cover decreased detrital energy input via leaf litter, it increased

incident solar energy (ultraviolet and photosynthetically active), which increased algal production. In response, benthic algae, most insect taxa, and juvenile salmonids density increased in manipulated streams. Stable isotope analysis found a predominant contribution of algal-derived energy to salmonid diets in manipulated reaches. The experiment found that reductions in riparian cover, under circumstances where it did not raise water temperature, strongly affected salmonids via increases in the energy content of river food webs. The author concluded that species-based management strategies can have unanticipated indirect effects on the target species, in this case salmonids, via the associated food web, and suggested that ecosystem-based management approaches may be useful for restoring depleted salmonid stocks.

An experiment to evaluate the effectiveness of riparian forested buffers, required by Washington Forest Practices on non-fish-bearing streams, was started in western Washington in 2006 (McIntyre et al. 2018). One of the study's 17 experimental sites is on the OESF. The study examines effects of different riparian buffers within harvested areas on riparian vegetation, stream temperature, instream wood, litterfall, detritus, nutrients, periphyton, macroinvertebrates, amphibians, and fish. Even small decreases in stream shade of <10 percent caused measurable increases in summer maximum stream temperature, with increases in maximum, minimum, and diel range of daily stream temperatures seen at nearly all treatment sites. Total P concentrations did not change significantly postharvest, but total N and NO_3^- were elevated significantly in response to harvest treatments. Studies of trophic pathways using C and N stable isotopes found no change in the contribution of algae to the stream trophic webs despite substantially increased light reaching the streams. A possible explanation for the lack of response was that the trophic structure in these small streams was so tightly coupled to the bordering terrestrial environment that increased light did not stimulate instream plant growth (McIntyre et al. 2018).

Natural disturbances such as debris flows and windthrow probably have effects on stream water quality, including N and P, but these effects have not been studied on the western Olympic Peninsula. Simulations of climate change effects on hydrology for the Olympic Peninsula predict significantly elevated stream temperatures, a shift from rain and snow transient runoff to a rainfall-dominated regime, more severe summer low flows, and more intense winter flooding (Mantua et al. 2010). Although such changes in physical conditions will likely have significant effects on water quality and on aquatic biota, including salmon, detailed predictions of such responses to climate change are not available for this region.

Research Needs

The research need of highest priority for regulatory agencies that could be filled at the OESF is a better understanding of the effects of alternative forest management practices on critical features of salmonid habitat, including stream water temperature, sediment production and routing through streams, and instream wood loading and function. Filling this need would improve regulators' understanding of the effectiveness of conservation measures, such as riparian buffers and forest road restoration and abandonment, and will aid in improving regulations aiming to protect critical salmonid habitat in northwestern streams. Filling this need would require implementing a range of harvesting regimes and stream protection practices, and systematically measuring their effects on salmonid habitat attributes. Within the OESF, WADNR has the ability to vary riparian buffer widths not only for research but as a standard management practice (WADNR 2016b). This management flexibility allows the agency to implement a wide variety of operational-scale experimental treatments that could be useful for addressing this need.

Management experiments within the OESF would be most informative if they included the responses of stream biological communities, especially salmonid populations. Because the impacts of forest management activities on anadromous salmonids interact with other factors, such as natural disturbances, ocean conditions, and marine fisheries (Lawson 1993, Tschaplinski 2000), there is a need to parse out the relative contributions of these factors. The OESF long-term status and trends monitoring watersheds, including unmanaged reference basins, have high potential to generate data that will be useful for understanding the role of forest management in these processes.

Another research need of interest to regulators that could be investigated at the OESF, although of lower priority for regulators, is the effect of forest land management practices on nutrient concentrations, fluxes in streams and wetlands, and instream processing and sequestration of stream nutrients, especially as they affect salmonids.

Potential Utility to Water Quality Regulatory Agencies

Regulatory agencies could use datasets and research from the OESF for developing a nutrient loading model that uses remote-sensing data and management information about watersheds to predict a nutrient transport rate in terms of kilograms of nutrients per hectare as a function of stand age, forest vegetation type, soil type, elevation/climate, road density, slope, management practices, and other factors. Such a model could be used to estimate how planned forest management activities

would affect nutrient loading to water bodies at the scale of hydrologic unit code 12 subwatersheds. Developing such a model might draw upon existing OESF datasets, including long-term monitoring of streamflow and stream nutrients, forest vegetation inventories, results of forest management experiments and remotely sensed data such as LiDAR and aerial photos.

Research on the effects of forest management on water quality and other public resources, conducted on the OESF and neighboring lands, have been used as the best available science in the development of state forest practices rules (Washington State Legislature, Title 222 WAC, 2017). The OESF will continue to have an important role in testing the effectiveness of the rules and developing best management practices for forest management by providing scientific information from ongoing studies, as well as providing a land base for research. State lands on the OESF are amenable to conducting research on forest management activities because of the existing flexibility to perform a variety of potential management activities, the availability of rich data systems for operational and forest inventory records, the ability to maintain sample sites longer than private timber companies, and the availability of long-term reference sites within or near WADNR lands.

OESF research examining the effect of forestry on water quality and associated aquatic species could be useful to future updates of the state's water quality criteria. The reference watersheds on OESF, ONP, and ONF that are monitored by WADNR might provide valuable information on spatial and temporal natural variation of key water quality constituents. Research results on N and P biological dose response in Olympic Peninsula streams under different riparian vegetation could be useful to regulatory agencies for developing water quality criteria for Coast Range rivers. There are currently no information systems or processes that link the OESF data to regulatory agencies such as WADOE. WADNR might work with state regulators to assess how data from the OESF can be better used to help inform the improvement of forest practices. For example, WADOE might partner with WADNR to add the OESF network of long-term managed and reference monitoring streams to the WADOE Watershed Health Database (WADOE 2017a). Standardizing monitoring protocols and data management procedures would probably be required to make OESF data compatible with WADOE needs.

Streamflow monitoring data from the OESF, combined with the long-term river monitoring data from local river monitoring stations, can be used in drought forecasting. A statewide flow monitoring system is used to forecast runoff volume (WADOE 2017b) and to determine when conservation actions are needed in response to droughts, for example, when to stop stream fish distribution sampling.

Reliability and Limitations of Findings

Monitoring data on stream habitat attributes such as stream temperature, channel morphology, discharge (in 10 basins), instream wood, riparian vegetation, and microclimate (in 10 basins) from the same 62 monitored watersheds are collected following peer-reviewed monitoring protocols, including detailed quality assurance/quality control field and data management procedures (Minkova and Foster 2017).

Research findings and monitoring data from the OESF are probably applicable to forested watersheds in the Coastal Range of Oregon, Washington, and British Columbia. Results of OESF management experiments may be applicable across the region where management practices implemented by other land managers are similar to those tested on the OESF, for example riparian management by Washington's private landowners or by federal land managers under the Northwest Forest Plan. The degree to which OESF data and science findings predict conditions at other locations may depend on factors such as similarities in biophysical conditions and land use history. Where high reliability is required, similarity analysis and validation experiments are suggested to test how well data from the OESF fit local conditions.

Key points:

- The OESF has recently established long-term monitoring of 62 small watersheds in an area large enough to investigate landscape-scale effects of ongoing forest management on streams.
- Reference study watersheds, with minimal onsite human disturbance, have been established on the OESF, neighboring ONP, and ONF lands where long-term monitoring of stream habitat conditions and fish populations has started.
- Historically, long-term monitoring of water quality in this region has mostly been on main-stem rivers although smaller streams represent a disproportionately larger part of the stream networks.
- The highest priority research need of the regulatory community that could be filled at the OESF is an improved understanding of the effects of forest management practices on critical features of salmonid habitat, including stream temperature, fine sediment loading, and instream wood and food supply.
- Existing OESF datasets and research results may be useful to regulatory agencies for practical purposes such as developing state forest practices rules and water quality criteria.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

There are no current water quality concerns about nutrients other than N and P in this region (Eilers et al. 1994, Lum 1986). However, early signs of a potential future issue may be high levels of mercury (Hg) that have been observed in trout from high-elevation lakes (Landers et al. 2008, Moran et al. 2007) and in largemouth bass in low-elevation Lake Ozette and Lake Dicky (Furl et al. 2010) on the Olympic Peninsula. These elevated Hg concentrations were suspected to be caused by air masses arriving from east Asia (Jaffe et al. 2005, Stottlemeyer et al. 2002, Wilkening et al. 2000) or by increased sedimentation from logging (Furl et al. 2010). Hg, in the form of methylmercury (MeHg), is a neuro-toxin that is concentrated by aquatic food chains to which humans can be exposed by eating contaminated fish. Although Hg is not a nutrient, findings from other parts of the country, including Marcell Experimental Forest (see chapter 2), suggest that atmospheric deposition of sulfate (SO_4^{2-}) may increase production of MeHg in wetlands (Jeremiason et al. 2006). If air pollution originating from Asia continues to increase, the effects from atmospheric deposition of Hg and SO_4^{2-} on water quality in the Pacific Northwest might be significant.

Findings From Studies

Long-term monitoring of nutrients other than N and P in atmospheric deposition has been consistently conducted on the western Olympic Peninsula, but stream water monitoring of these nutrients has been intermittent (table 12.1 and fig. 12.1). The ONP has regularly monitored precipitation at the Hoh Ranger Station for SO_4^{2-} , hydrogen ion (H^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), and chloride (Cl^-) as part of NADP since 1980. Stream and precipitation chemistry, including bicarbonate (HCO_3^-), K^+ , Mg^{2+} , Cl^- , SO_4^{2-} , Ca^{2+} , and Na^+ , were collected in West Twin Creek from 1984 to 2004 and Linder Creek from 1999 to 2004 (Stottlemeyer et al. 2002). Stream water quality, including measurements of HCO_3^- , Ca^{2+} , Na^+ , K^+ , Cl^- , and several metals, in main-stem rivers was monitored intermittently by the USGS, in the Hoh (1960–1980), Calawah (mid-1970s), and Queets (1977–1993) River. A water quality assessment of the Hoh River watershed from 1977 through 1980 measured Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , HCO_3^- , and SiO_2 at 13 sites in the main-stem and 12 sites on tributaries (Lum 1986). Wootton and Pfister (2012) collected DOC in nine streams from the northern part of the OESF in 2001 and again in 2010 to estimate stream inputs to near-shore waters.

Short-term studies have investigated nutrient cycles and biological processes involving nutrients other than N and P within the Hoh River basin. From the study

of West Twin Creek, Edmonds et al. (1998) found that precipitation chemistry was dominated by Na^+ and Cl^- of marine origin, while stream chemistry was dominated by Ca^{2+} and SO_4^{2-} that typically results from rock weathering. They also reported that marine-related nutrients Cl^- , SO_4^{2-} , Mg^{2+} , and Na^+ were highest in precipitation near the ocean.

Volk (2004) found that nutrient concentrations in fresh leaf litter decreased by 36 to 67 percent for Ca^{2+} , copper, K^+ , Mg^{2+} , manganese, and strontium (Sr^{2+}) as it aged over 18 days in streams with alder-dominated riparian vegetation. In hemlock-dominated streams, the concentration of iron and zinc in fresh leaf litter significantly increased.

Brenkman et al. (2007) studied the relationships between bull trout otolith element ratios and water chemistry to investigate migration between near-shore marine environments and aquatic habitats in the Hoh River watershed. They found Sr/Ca was higher in otolith layers from fish while they were in salt water compared to periods when the fish were in freshwater. This provided evidence that these stream fish spent significant portions of their life cycle in the ocean.

Other Factors Relevant to Stream Nutrients Other Than N and P

Studies and monitoring within the OESF of other environmental factors that might limit biological responses to nutrients other than N and P are the same as reported earlier in this chapter for nutrients N and P. The water chemistry monitoring initiated by WADNR and The Evergreen State College in 2016 in a subset of watersheds monitored for status and trends of habitat conditions (Minkova et al. 2012) includes DOC, which is a source of energy in trophic webs and may affect responses to nutrients.

Dose-Response Studies

Dose-response studies for nutrients other than N and P have not been conducted on the OESF.

Reference Watersheds

See the description of the monitored reference watersheds located in the OESF, ONP, and ONF described under nutrients N and P.

Cross-Site and Regional Studies

Long-term atmospheric deposition of SO_4^{2-} , H^+ , Ca^{2+} , Mg^{2+} , K^+ , Na^+ , and Cl^- , collected at the Hoh Ranger Station in proximity to the OESF, has been used in nationwide analyses of atmospheric deposition by the NADP (NADP 2019a). These analyses showed that atmospheric deposition of nutrients of nonmarine origin are

very low, as is typical of coastal areas downwind of the Pacific Ocean, and remote from local sources of air pollution. However, an assessment of ecological and biological effects of hazardous air contaminants in 20 national parks in the Western United States and Alaska found that fish Hg concentrations in the ONP were among the highest of all parks sampled (Landers et al. 2008).

Responses to Management and Natural Disturbances

Murray et al. (2000) compared the changes in concentrations and seasonal patterns of stream nutrients, other than N and P, on two partially harvested watersheds in the OESF and the Twin Creek reference site on the ONP. Overall, the partial harvesting had little influence on Na^+ , Cl^- , Ca^{2+} , K^+ , and Mg^{2+} 11 to 15 years postharvest. Cation concentrations were generally higher in the old-growth watershed. The differences were attributed partially to the sites' physical differences such as aspect and distance from the ocean, and possibly in part to differences in canopy cover and streamflow between harvested and unharvested sites.

Reliability and Limitations of Findings

Research findings and monitoring data from the OESF, related to nutrients other than N and P, are probably applicable to forested watersheds in the coastal ranges of Oregon, Washington, and British Columbia. OESF results may be extrapolated broadly across the region to areas where the management practices implemented by local land managers are similar to those tested on the OESF. The extent to which OESF data and science findings predict conditions at other locations may depend on factors such as similarities in biophysical conditions and land use history. Where high reliability is required, similarity analyses and validation experiments or monitoring are suggested to test how well data from the OESF fit local conditions.

Research Needs

The highest priority research need of the regulatory community related to nutrients other than N and P that might be filled at the OESF is, What are the levels and trends of Hg in aquatic food chains in low-elevation waters of the western Olympic Peninsula, and are they being affected by atmospheric deposition or forest management?

Better stream data on Hg levels and trends would be important to regulatory agencies for developing regulations or management guidelines that better protect human health from hazardous exposure to environmental Hg. Deposition of Hg and SO_4^{2-} might also be sensitive indicators of potential impacts of atmospheric

transport from distant sources in Asia. Filling this need at the OESF would require continuing current NADP monitoring of atmospheric deposition of SO_4^{2-} and adding monitoring of Hg deposition. Regular monitoring of Hg in aquatic food chains and SO_4^{2-} in the OESF streams affected by various forest management treatments and OESF, ONF, and ONP reference streams would also need to be established. If high levels or increasing trends of Hg were detected, further investigations of environmental sources that introduce Hg into food chains might be warranted.

Another research need of interest to regulators, but of lower priority, is additional information on cloud water deposition of nutrients to coastal forests, which may contribute to nutrient cycling and potential pollution effects in the region (Bormann et al. 1989).

Potential Utility to Water Quality Regulatory Agencies

The OESF and neighboring ONF and ONP could be suitable sites for regulatory agencies to use for the early detection of effects from long-range pollution as these sites have few confounding local sources of air pollution. Existing long-term monitoring datasets of nutrients, such as SO_4^{2-} -S in stream water and atmospheric deposition at the OESF and ONP, are examples of early warning signals that regulatory agencies could use for potential impacts on regional streams from long-range atmospheric transport of pollutants from Asia.

The OESF is also well suited as a study site to investigate the effects of forest management practices on stream water quality, including nutrients other than N and P, and will continue to provide data and a land base for scientific investigations that test the effectiveness of forest practices rules and develop best management practices for forest management.

Key points:

- There are currently no pressing concerns regarding nutrients other than N and P in the forested streams on the western Olympic Peninsula.
- The only study that has been done at the OESF to examine effects of forestry practices on stream nutrients other than N and P (Murray et al. 2000) found no effects.
- The highest priority research need of regulatory agencies, related to nutrients other than N and P would be intensive monitoring of Hg in aquatic food chains and studies to assess how environmental factors, such as forest land management and atmospheric deposition of Hg and the nutrient sulfur, may influence human exposure to this neurotoxin.

Overview and Synthesis

The OESF offers extraordinary advantages as a site for scientifically investigating issues of concern to regional water quality regulatory agencies. The OESF is unusual among EFRs because it encompasses a land base large enough to do landscape-scale investigations of effects of replicated land management treatments on streams. The OESF is actively managed to produce timber, and its manager, WADNR, has considerable latitude to use this land management as an experimental tool for investigating effects on streams. The extensive operational records, forest inventory data, and other ecological information are public and readily available to researchers. Unlike many other parts of the Pacific Northwest, where multiple ESA-listed anadromous fish runs tightly constrain management experiments, the relatively healthy condition of runs at the OESF provide opportunities to test a wider range of experimental treatments and to study not only effects on habitat but also on fish. Furthermore, as a member of the EFR network, the OESF can draw upon the deep pool of scientific and technical expertise built over many decades within the network. These assets combine to make the OESF an important field research laboratory for investigating critical issues in this region, such as the effects of forest land management on riparian habitat and anadromous fish.

The OESF aquatic and riparian monitoring in 50 managed and 12 reference watersheds is designed to produce long-term environmental data and to provide a research platform on which a variety of forest management experiments can be implemented. For example, the effects of forest management practices with varied intensities and spatial and temporal patterns can be tested on riparian vegetation, nutrients, and vertebrate and invertebrate assemblages in streams and wetlands. The extensive environmental and land use datasets maintained by WADNR create a baseline of pretreatment conditions and an estimate of variability of habitat attributes that can be used for “before and after” assessments. The 12 reference watersheds that are managed for minimal onsite human disturbance are well-suited for long-term ecological monitoring both to investigate effects of natural disturbances, such as climate change, and for parsing the effects of natural disturbances from those of management.

The WADNR-led stream research and monitoring at the OESF is an integral part of the state trust lands adaptive management process, which will use scientific findings as feedback to continuously improve management practices. Empirical data and research findings about ecological relationships and management effects will be used to refine the models used in forest land planning, to reduce uncertainties in the analyses of environmental effects, and to test habitat recovery projections in existing management plans. The lessons learned from applying adaptive man-

agement on the OESF have the potential to be useful to forest managers from other organizations, for example, on federal lands under the Northwest Forest Plan and private lands regulated by Washington forests practices.

Water quality regulatory agencies might benefit if they developed cooperative relationships with WADNR to plan and implement studies at the OESF that address questions that are of high priority to regulators.

Key points:

- A large, dedicated land base, flexible management mandate, and landscape-level research approach combine to make the OESF a potentially important source of scientific information for water quality regulatory agencies.
- The highest priority science needs of regulatory agencies that might be filled at the OESF would be an improved understanding of alternative harvest management practices that would provide better protection for water quality and aquatic biota, and a better understanding of sources of Hg in aquatic food chains such as land management and atmospheric deposition of Hg and the nutrient sulfur.
- Existing environmental monitoring datasets and research from the OESF might be of immediate use to regulatory agencies, and additional benefits might be gained by cooperating with WADNR to plan and implement experiments on the OESF that address questions of high regulatory interest.

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

Mary Beth Adams and Gregory W. Cook¹

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. 39° 3' 15" N, long. 79° 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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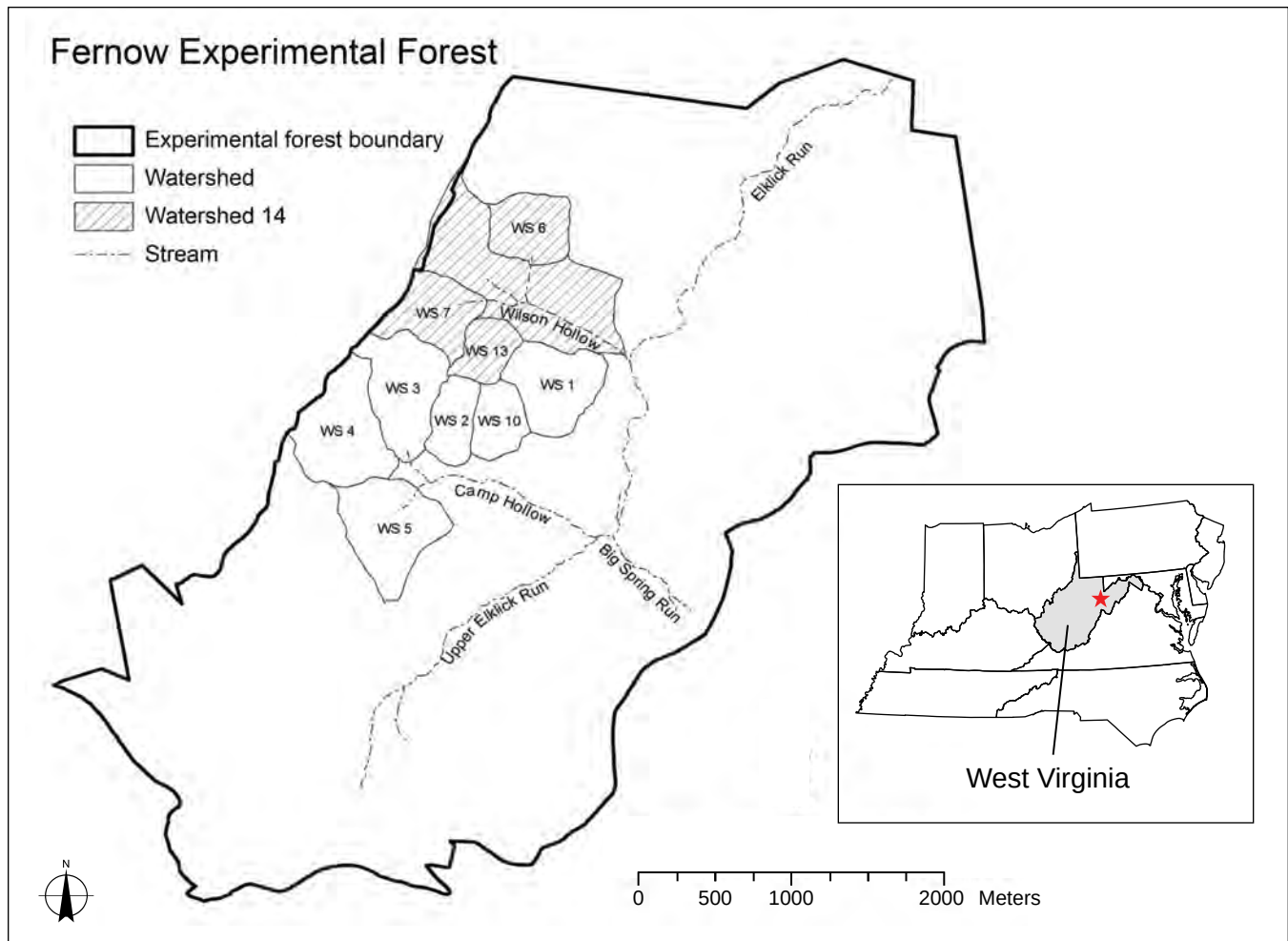


Figure 13.1—Fernow Experimental Forest with study watersheds (WS) and main-stem streams.

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 ($[\text{NH}_4]_2\text{SO}_4$) 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 $(\text{NH}_4)_2\text{SO}_4$ 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 $\mu\text{g NO}_3^-/\text{N/L}$ (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 $(\text{NH}_4)_2\text{SO}_4$ 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, $(\text{NH}_4)_2\text{SO}_4$ 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 $(\text{NH}_4)_2\text{SO}_4$ 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 $(\text{NH}_4)_2\text{SO}_4$, 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 $(\text{NH}_4)_2\text{SO}_4$ 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/m² in the highest pH stream to 1.19 g dry mass/m² 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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Chapter 14: Ecoregion 8.4.4 Blue Ridge: Coweeta Hydrologic Laboratory, North Carolina

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Introduction

Research involving nutrients and biogeochemistry has a long history at the Coweeta Hydrologic Laboratory (CHL). The majority of nutrient research has focused on nitrogen (N), phosphorus (P), and dissolved organic carbon (DOC), and less so on other nutrients such as calcium (Ca). This chapter reviews research at the CHL on watershed biogeochemistry and stream organismal and ecosystem responses to nutrient enrichment, with primary attention to N and P. It also identifies future research at CHL that could fill science gaps that are of high priority for regulators and suggests ways that regulators might use existing science findings and datasets from CHL.

Site Description

CHL is located in southwestern North Carolina in the Blue Ridge Province of the southern Appalachians (Swank and Crossley 1988). CHL (lat. 35° 03' 35" N, long. 83° 25' 48" W) was established in 1934 near Otto, North Carolina, on 2185 ha of federal land that has been dedicated to research within the Nantahala National Forest (NNF). The CHL encompasses Shope Fork and Ball Creek basins, which together form the Coweeta Creek basin and also includes the adjacent Dryman Fork basin (fig. 14.1). Elevations range from 675 to 1592 m (Swank and Crossley 1988).

Forest types—

Vegetation at CHL includes northern hardwoods, cove hardwoods, xeric oak/pine, oak/hickory, and mixed-oak forests (Boring et al. 2014). Forests are diverse as is typical for southern Appalachian plant communities. Tree species are distributed predictably over the variable topography and follow a moisture gradient (Day et al. 1988). The plant communities at CHL are dynamic and change over time (Elliott et al 1999). Following the loss of American chestnut (*Castanea dentata* (Marshall) Borkh.) owing to chestnut blight beginning around 1925, CHL changed from an oak-chestnut-dominated community to a predominantly oak-hickory forest (Elliott and Swank 2008). The current forest is dominated by deciduous oaks (*Quercus*

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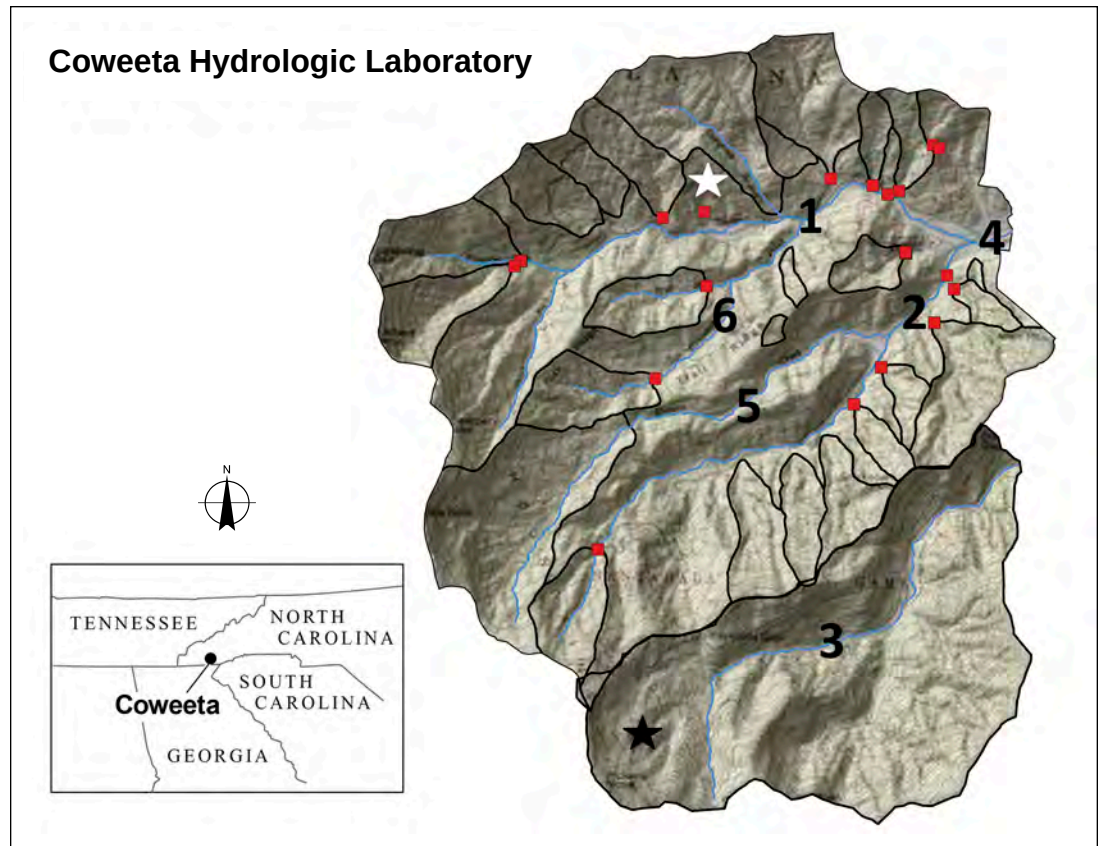


Figure 14.1—Coweeta Hydrologic Laboratory (CHL) in southwestern North Carolina with numbers indicating major streams: (1) Shope Fork, (2) Ball Creek, (3) Dryman Fork, (4) Coweeta Creek, (5) Henson Creek, and (6) Cunningham Creek. Red squares locate stream weirs. Black lines identify study watershed boundaries. Whole-stream nutrient additions were performed in Shope Fork watershed (white star), and Dryman Fork watershed (black star). Map courtesy of the Coweeta Long Term Ecological Research, KC Love, cartographer. Terrain imagery courtesy of ESRI Inc., under Creative Commons License CC BY-NC-SA 3.0.

spp.), tulip poplar (*Liriodendron tulipifera* L.), and maple (*Acer* spp.), with an evergreen understory of great laurel (*Rhododendron maximum* L.) and mountain laurel (*Kalmia latifolia* L.) (Boring et al. 2014).

The vicinity of CHL was lightly disturbed by American Indians prior to European-American settlement, primarily by seasonal understory burns. After the 1840s, European-American settlers burned and grazed uplands and cultivated crops in some valley bottoms (Douglas and Hoover 1988). Most of the basin was logged between 1900 and 1923 when 8 million board feet of timber were harvested (Elliott and Swank 2008). The heaviest cutting occurred at lowest elevations, in valleys, and accessible coves. Since establishment as an experimental site, human disturbances within CHL have been restricted to research purposes and have been well documented by the U.S. Forest Service (USFS) (Day et al. 1988, Elliott and Swank 2008).

Stream types—

First- through fifth-order streams drain 16 gaged catchments ranging in area from <5 to 760 ha (Benstead and Leigh 2012, Swank and Crossley 1988) (fig. 14.1). Most of the 73 km of streams within the CHL basin are first and second order (Meyer et al 1993). Ball Creek and Shope Fork, both fourth-order streams, join within the CHL boundaries to form Coweeta Creek, which flows east into the Little Tennessee River. Stream gradients are relatively steep, ranging from 15 to 30 cm/m (Meyer et al. 1993). Stream substrate varies along a longitudinal gradient with varying proportions of bedrock outcrops, boulders, cobble, gravel, pebble, sand, and silt (e.g., Wallace et al. 1999). Maximum average depth to bedrock below stream bottom is 10 cm. Low-order streams are shaded throughout the year by a dense understory of *R. maximum*. Large and small woody materials in the stream channel are abundant and form instream debris dams at all elevations. Headwater streams at CHL support a minimum of 290 plant and animal taxa, including 145 insect genera and roughly 50 diatom and algal species, making CHL streams moderately diverse habitats (Lowe et al. 1986, Meyer et al. 2007). Lower elevation streams have low to moderate densities of fish, including mottled sculpin (*Cottus bairdi* Girard), longnose dace (*Rhinichthys cataractae* Valenciennes), rainbow trout (*Oncorhynchus mykiss* Walbaum), and brook trout (*Salvelinus fontinalis* (Mitchill)) (Freeman et al. 1988).

Soils—

The underlying bedrock is dominated by metasandstone and schist (Velbel et al. 1988). Soils are immature Inceptisols and older Ultisols (Swank and Crossley 1988, Thomas 1996, USDA NRCS 2015). Soil depth decreases with increasing elevation.

Climate—

The climate is classified as marine, humid temperate (Cfb) based on Köppen's climate system (Swift et al. 1988). Average annual air temperature is 13 °C. Growing season is early May to early October. Average annual rainfall is 1700 mm at low elevations to 2500 mm at high elevations (Swank and Webster 2014). Average monthly precipitation is greatest in March and lowest in the fall, although tropical storms in autumn have produced record rainfalls.

Research History

Research at CHL originally tested theories in forest hydrology as put forth by C. R. Hursh in 1938 (Douglass and Hoover 1988). From 1934 to 1968, baseline data were collected to investigate effects of various land use practices, such as logging and cattle grazing, on water yield and water quality, such as turbidity. Later, these data

provided a base on which to develop watershed-scale ecosystem studies. Research at CHL has been conducted under two main philosophies: (1) the quantity, timing, and quality of streamflow provide an integrated measure of the success or failure of land management practices; and (2) good resource management is synonymous with good ecosystem management (Swank and Crossley 1988).

In the early to mid-20th century, a suite of watershed management treatments was studied at CHL, consisting of several watershed timber cuttings, species conversions, and a prescribed burn. Swank and Crossley (1988) summarized the early watershed manipulations. Beginning in the 1970s, USFS scientists at CHL began collaborating with university scientists to address questions focusing on watershed nutrient cycling. This work was initially funded by the National Science Foundation (NSF) through the Institute for Broadening Participation program. In 1974 CHL scientists began an interdisciplinary study examining the effects of clearcut cable-logging to test hydrologic and ecological hypotheses and provide data relevant to forest land managers. In 1980, CHL became one of the original study sites in the NSF Long Term Ecological Research (LTER) program. In this program, investigator-led research projects, and USFS research cooperated to build an expanded ecological research program at CHL.

Stream ecosystem research began in the late 1960s at CHL, mostly in collaborations with universities, including the University of Georgia, Virginia Polytechnic Institute and State University, and North Carolina State University (Meyer et al. 1993, Tebo 1955, Woodall and Wallace 1975). During the 1980s, stream research focused on streams draining small catchments, including effects of drought on ecosystem structure and function (Wallace et al. 1991), clearcutting (Haefner and Wallace 1981, Swank and Webster 2014), stream macroinvertebrate removal (Cuffney et al. 1990, Lugthart and Wallace 1992), and debris-dam additions (Wallace et al. 1995). In the 1990s, research expanded spatially to include larger streams in the Coweeta basin. A study on Ball Creek examined the effects of gradients in geomorphology on ecosystem structure and function (e.g., Huryn and Wallace 1988). Research also shifted to focus on the controls of nutrient cycling and retention (Munn and Meyer 1990, Webster et al. 1991).

From the mid-1990s to the present, CHL streams became model systems to examine carbon (C) and nutrient limitation of detritus-based streams using whole-stream manipulations of nutrients and C inputs. Stream experimentation included litter exclusion, wood removal, leaf addition (Eggert and Wallace 2003a, Wallace et al. 1997a), riparian rhododendron removal (Yeakley et al. 2003), and stream nutrient additions (Cross et al. 2006, Rosemond et al. 2015). In the early 2000s, the focus of the LTER stream research program expanded beyond the Coweeta Creek basin to include a

comprehensive study of drivers and effects of land use change across the southern Appalachians, focusing on the Little Tennessee River basin (Hagen et al. 2006).

Availability of Publications and Data

A complete CHL bibliography and searchable bibliographic database and a data file catalog can be found on the Coweeta LTER website (Coweeta LTER 2017a, 2017b). Long-term daily climate and streamflow datasets from CHL, formatted for ready comparisons with other experimental forests and ranges (EFR) and LTER sites, can be downloaded from the ClimDB/HydroDB website (LTER Network 2017). Long-term atmospheric deposition monitoring data from CHL are available via the National Atmospheric Deposition Program (NADP) data portal (NADP 2019).

Biological Responses to Stream Nutrients N and P

Issues of Concern

In the southern Appalachians, high-elevation, forested basins such as CHL have historically been regional sources of clean water. However, atmospheric deposition of N is increasingly a major source of N enrichment, especially in mountainous areas, which CHL represents. Furthermore, residential development and agriculture are both major sources of N and P to streams at low to mid elevations of the region, and although they do not occur within the Coweeta basin, where these types of land uses occur at higher elevations, they increase nutrient loading. Stream nutrient enrichment can negatively affect the beneficial uses of headwater streams and downstream water bodies. Beneficial uses at risk in North Carolina and surrounding states include (1) supporting aquatic life, (2) primary recreation (swimming, diving, water skiing), (3) secondary recreation (fishing, boating, fish consumption), (4) trout waters, (5) municipal water supply, and (6) outstanding resource waters. Excess N and P can degrade water quality to the degree that it does not meet numeric criteria for chlorophyll *a* (chl *a*), dissolved oxygen, or nuisance growth of algae. This concern applies to the streams and lakes downstream of CHL, such as the Little Tennessee River and Fontana Lake, and to streams and lakes in the surrounding states of Georgia, South Carolina, Tennessee, and Virginia, which have similar criteria to protect beneficial uses.

Nutrient addition experiments at CHL have used headwater streams as model systems to test the effects of nutrient enrichment that occur in human-modified landscapes on detritus-based processes in streams. Investigations at CHL have focused on effects of N and P on detritus-based pathways in aquatic systems, which have been less studied than these effects on algal-based pathways (Smith and Schindler 2009).

Findings From Studies

Ambient nutrient conditions—

Streams at CHL are generally nutrient poor, characterized by low concentrations of nitrate (NO_3^-), ammonium (NH_4^+), and phosphate (Swank and Crossley 1988, Swank and Vose 1997). The dominant form of N in CHL streams is NO_3^- because of rapid biological uptake of NH_4^+ . Concentrations of NO_3^- range from ~10 to 200 $\mu\text{g/L}$ but are typically <100 $\mu\text{g/L}$ (Swank and Crossley 1988). Ammonium concentrations are typically <10 $\mu\text{g/L}$. Consequently, nutrient cycling in CHL streams exhibits high N uptake rates and thus tight nutrient cycling (Tank et al. 2000, Webster et al. 2003). Dissolved P concentrations in stream water are very low at CHL, typically <10 $\mu\text{g/L}$, thus streams also exhibit high P uptake rates (Mulholland et al. 1997). Mean annual rates of atmospheric deposition of inorganic N are ~6.1 and 7.2 kg N/ha/yr for low- and high-elevation watersheds, respectively. Annual deposition rates are increasing by ~0.084 kg N/ha/yr (Brookshire et al. 2011).

Effects of nutrients on stream carbon resources: detritus and algae—

As is common in closed-canopy forests, primary production by algae is light limited most of the year at CHL and contributes only a small fraction to the basal resources for consumers. Energy flow in streams at CHL is dominated by the decomposition of detritus, primarily plant leaf litter and wood, and is associated with heterotrophic bacteria and fungi (Hall et al. 2000, Wallace et al. 1997b). In these detritus-dominated systems, nutrient effects on detrital dynamics are more generally illustrative of effects on energy flow.

There have been two long-term whole-stream nutrient enrichment experiments conducted at CHL. The first study was conducted in watershed (WS) 53 and WS 54 using a paired-watershed approach (N + P experiment) (Suberkropp et al. 2010). N and P were added to one stream (WS 54) at an N:P ratio of 16:1 for 5 years (2000–2005) and responses compared to a reference stream (WS 53) (table 14.1). Both streams were sampled for 1 or 2 years pretreatment, depending on the response variable. The second study tested the relative importance of N and P on stream responses by adding nutrients to five streams in the Dryman Fork watershed for 2 years (2011–2013), with 1 year of pretreatment sampling (2010–2011; N × P experiment). Each of the five streams received different concentrations of N and P, resulting in a gradient of N:P ratios (Rosemond et al. 2015) (table 14.1). Other bioassays and short-term nutrient experiments have also been conducted in CHL streams (e.g., Tank and Dodds 2003).

Algal responses—

Although algal biomass is usually light limited at CHL, it may respond to nutrients under some circumstances. Nutrient enrichment experiments showed that responses in algal biomass occur during the spring months when irradiance is high or when riparian forest cover is reduced. For example, clearcutting of a watershed resulted in increased primary production, which led to increases in a grazing mayfly compared to a reference stream (Wallace and Gurtz 1986). However, a nutrient limitation study in the reference and clearcut stream found that although added N and P tended to increase algal biomass in the clearcut stream, differences observed were not significant (Lowe et al. 1986). This result corroborated that biofilms at CHL are primarily light limited (Lowe et al. 1986). Tank and Dodds (2003) found a similar nonsignificant increase in algal biomass in response to light in a separate study conducted during the fall in Ball Creek, which also found algal biofilms responded the most to P or N + P.

A 2-year continuous enrichment (N + P) of WS54 resulted in increased algal biomass chl *a* during the spring compared to a reference stream. However, another measure of algal biomass response, biovolume, did not significantly respond to enrichment, indicating higher chl *a*/cell (Greenwood and Rosemond 2005). In addition, enrichment increased algal growth rates, which is a proxy for productivity. The observed increase in chl *a*, even at peak biomass of 0.5 g ash-free dry-mass [AFDM]/m², still contributed only a very small portion to available resources compared to leaf litter standing crops (300 to 500 g AFDM/m²) (Greenwood and Rosemond 2005). This study highlights the potential limits to the stimulation of primary production by nutrient enrichment at CHL and similar forested streams, although higher light availability would result in a greater response. Additionally, the study by Greenwood and Rosemond (2005) found that experimental enrichment did not alter the species composition of algae at CHL following 2 years of continuous enrichment.

Resources such as algal biofilms and detritus can change in their nutrient content as algae, bacteria, or fungi increase in biomass or acquire relatively more N or P vs. C in their tissues. Changes in the relative nutrient content (stoichiometry) of biofilms or detritus, with altered water column nutrient availability, can result in higher quality food for consumers, and can affect ecosystem functions. In studies at CHL, the nutrient content of algal biofilms (as C:N and C:P ratios) responded significantly to enrichment. The C:P ratio of biofilm changed the greatest compared to a reference reach (C:P = 845 vs. 1741), followed by reductions in N:P and C:N ratios. This finding indicated that biofilm resources become more nutrient rich in response to increased dissolved nutrient availability and that P content changed

more than N content (Rosemond et al. 2008). Changes in biofilm nutrient content at CHL are consistent with several studies that show algal biofilms have relatively flexible stoichiometry (Stelzer and Lamberti 2002, Taylor et al. 2014) and increase in nutrient content when levels of water column nutrients rise.

Collectively, these studies suggest that when light is sufficient, such as during spring, streams at CHL appear to be nutrient limited and algae can respond to increased nutrient availability. Additionally, these studies show that the nutrient content of algal resources can respond to nutrient enrichment, which can have important implications for the quality of food to consumers.

Heterotrophic microorganisms and detrital dynamics—

Experimental nutrient enrichments at CHL have revealed strong effects on leaf litter breakdown and C dynamics. Enrichment of a stream with N and P at a target N:P ratio of 16:1 (table 14.1) increased breakdown of leaf litter two- to threefold compared to reference conditions for both red maple (*Acer rubrum* L.) and rhododendron (*Rhododendron* L.) litter (Greenwood et al. 2007, Gulis and Suberkropp 2003). The breakdown rate was greater for rhododendron, which has a lower initial

Table 14.1—Nutrient concentrations and years of treatment for the N + P and N × P enrichment experiments

	Stream ^a	Year	Treatment ^b	SRP	DIN
		(July–July)		(µg/L)	(µg/L)
N + P experiment	WS 53	1999–2000	PRE	6.8 ± 3.0	23.2 ± 8.5
		2000–2005	REF	8.0 ± 1.3	31.0 ± 3.4
	WS 54	1999–2000	PRE	9.5 ± 2.3	29.3 ± 4.9
		2000–2005	ENR	80.0 ± 5.6	506.2 ± 36.3
N × P experiment	2:1	2010–2011	PRE	2.9 ± 0.2	18.1 ± 1.5
		2011–2013	ENR	47.5 ± 4.3	75.4 ± 7.5
	8:1	2010–2011	PRE	2.5 ± 0.2	111.6 ± 17.3
		2011–2013	ENR	47.8 ± 8.0	180.8 ± 15.8
	16:1	2010–2011	PRE	3.0 ± 0.5	37.4 ± 5.7
		2011–2013	ENR	35.6 ± 3.8	307.5 ± 40.8
	32:1	2010–2011	PRE	3.1 ± 0.3	188.8 ± 14.4
		2011–2013	ENR	20.1 ± 2.6	314.5 ± 41.7
	128:1	2010–2011	PRE	2.5 ± 0.2	56.6 ± 7.8
		2011–2013	ENR	7.1 ± 0.8	303.0 ± 34.5

For the N × P experiment, stream numbers represent target N:P ratios. Values for WS53 and WS54 are from Davis et al. (2010a).

^a Five streams in the Dryman Fork watershed were enriched for 2 years at different concentrations of N and P and N:P ratios. WS54 was enriched with nitrogen + phosphorus (N + P) at 16:1 N:P ratio from 2000 to 2005.

^b Treatment indicates the concentration of soluble reactive phosphorus (SRP ± SE) or dissolved inorganic nitrogen (DIN ± SE) during pre-enrichment (PRE), reference conditions, or enriched (ENR) periods.

nutrient content. In the $N \times P$ experiment, breakdown rates increased for maple and rhododendron in all treatments 2.2- and 4.9-fold on average, respectively. Stream water N and P concentrations were roughly equivalent predictors of breakdown rate, and mechanistic pathways of nutrient effects occurred via both microbial biomass and shredder biomass (Manning et al. 2015). A ~sixfold increase in breakdown rate was also reported for standardized wood veneers in the $N + P$ experiment, but this effect was less pronounced on maple twigs, which have a lower surface:volume ratio compared to veneers (Gulis et al. 2004). Overall, the magnitude of response of wood was greater than that of leaf litter.

As a result of increased breakdown rates, nutrient enrichment drastically reduced leaf litter standing crops at the reach scale in both enrichment experiments. Summer minima of standing crops were much lower and occurred much sooner than in reference conditions (Rosemond et al. 2015, Suberkropp et al. 2010). Standing crops were reduced in the summer to an extent (<50 g AFDM/m²) which may have negative consequences for secondary production of macroinvertebrates in the long term (Eggert and Wallace 2003b). The rate of whole-stream litter loss increased by ~58 percent, and N and P concentrations had approximate additive effects on the loss of detrital standing crops (Rosemond et al. 2015). Moreover, the effect of enrichment on leaf litter standing crops was retained across a discharge gradient of <1 to 20 L/s. Related to these findings, Benstead et al. (2009) reported increased fine particulate organic matter (FPOM) export in the enriched stream compared to the reference stream in the $N + P$ experiment. Increased FPOM export indicates that a higher proportion of particulate C is transported downstream instead of being used by organisms; and also reflects increased shredder activity. Ultimately, these studies show that nutrient enrichment accelerates reach-scale loss of detrital C owing to more rapid export of particulate C, which reduces storage of a vital energy resource.

The effects of nutrients on emergent stream functions, such as litter breakdown rates and retention of C, are due to the responses of heterotrophic bacteria and fungi to increased nutrients. These microorganisms are important components of food webs at CHL (Hall et al. 2000). Fungi colonize detritus when it enters a stream, alter detrital stoichiometry by taking up nutrients, and contribute to decomposition via mineralization of leaf C. Fungal biomass and production increased on leaf litter in response to added nutrients in the $N + P$ experiment, which led to higher microbial respiration rates and thus contributed to increased rates of litter breakdown (Gulis and Suberkropp 2003, Suberkropp et al. 2010). Fungal biomass and respiration rates increased on leaf litter to a greater extent than bacteria increased on FPOM (Tant et al. 2013). At Hubbard Brook Experimental Forest (HBEF) (chapter 3), fungal biomass and respiration rates on leaves vs. wood showed a

similar response to nutrient enrichment (Stelzer et al. 2003). Bioassays comparing responses of microbial biofilms in reference and litter-excluded streams at CHL found that fungal biomass was co-limited by N and P (Tank and Webster 1998), although another bioassay study found fungal biomass in Ball Creek to be primarily P limited (Tank and Dodds 2003).

Similar to algae, the nutrient content of detritus increased in response to experimental nutrient addition (Rosemond et al. 2008). The quality of detritus for consumers is largely driven by its nutrient content, particularly the ratio of C:N:P, which is important for both C loss rates and detritivores. Several studies indicate that nutrient enrichment generally reduces the C:N or C:P of detritus (Cross et al. 2003, Tant et al. 2013). In the N + P experiment at CHL, enrichment reduced bulk leaf litter C:P by 37 percent and N:P by 42 percent, but C:N showed little change over 2 years of enrichment (Rosemond et al. 2008, Tant et al. 2013). In the N × P experiment, enrichment altered litter stoichiometry, with the greatest effect again being reduced C:P of litter, although C:N was also reduced (Manning et al. 2015). Litter N content increased with fungal biomass, and litter P content increased with stream water P concentration. Effects of enrichment on litter stoichiometry were found to occur via subtly different mechanisms for N and P, and those mechanisms drove microbial and invertebrate responses to enrichment (Manning et al. 2015). Findings at CHL are consistent with studies that found strong positive linkages between dissolved P concentrations and detrital P content by examining landscape gradients in stream nutrient concentrations in the U.S. interior highlands and Costa Rican tropical streams (Scott et al. 2013, Small and Pringle 2010).

Collectively, results of studies at CHL indicate that nutrient enrichment stimulated breakdown rates of leaf litter, and reduced overall storage of organic matter. Litter that is available to consumers was of higher quality owing to lower C:nutrient ratios. N and P both contribute to increases in litter breakdown and fungal responses. However, stream water P created stronger responses in detrital P content. These responses have important consequences for stream biota as well as downstream nutrient and C dynamics.

Effects of nutrients on macroinvertebrate biomass and production—

Experimental nutrient additions at CHL have shown clear effects on biomass and production of macroinvertebrates, altered assemblage size structure, and altered food web structure. After 2 years of experimental enrichment of N + P, secondary production of the entire macroinvertebrate assemblage approximately doubled relative to a reference stream (Cross et al. 2006). This response was lower for long-lived species because they likely faced resource limitation resulting from depletion of detritus and have longer generation times (Cross et al. 2005). Higher shredder

biomass was found in leaf packs during this same experiment (Greenwood et al. 2007). The response was mediated by a near doubling of the flows of C, N, and P from basal resources to macroinvertebrates associated with an increased proportion of detrital C consumed (14 percent pretreatment vs. 35 percent during enrichment) (Cross et al. 2007).

In this study, increases in secondary production were primarily driven by reductions in the elemental imbalances between food resources and consumers. However, by the end of year 5 of enrichment, food web structure changed (Davis et al. 2010a): specifically, predator efficiency decreased in response to enrichment, as evidenced by a decreased proportion of primary consumers consumed. This occurred despite secondary production of primary consumers increasing 2.2-fold in the nutrient-enriched stream. The effect of increased primary consumer production did not result in increased production of macroinvertebrate predators over the long term. This was driven by increased dominance of a large-bodied shredding caddisfly (*Pycnopsyche gentilis*) that was largely invulnerable to predation because it builds stone cases in later instar stages. Additionally, long-term enrichment had a greater effect on larger bodied vs. smaller bodied primary consumers, shifting the size distribution of primary consumers. After 5 years of experimental enrichment, small-bodied primary consumer biomass was similar to pretreatment levels. Abundance of primary consumers also decreased to pre-enrichment levels, indicating that enrichment increased overall body size of consumers. Conversely, small-bodied predator biomass and abundance exhibited a positive long-term response to enrichment, while large-bodied predators did not (Davis et al. 2010b). Similar results were found across an urban nutrient gradient in which predator production did not track total primary production owing to the increase in large-bodied noninsect taxa that were invulnerable to predation (Johnson et al. 2013). Therefore, positive effects of enrichment on primary consumer production may not propagate to larger macroinvertebrate predators; instead “trophic dead ends” can be created if energy flow is diverted to a few dominant taxa.

Consumer nutrient content—

Experiments conducted at CHL were some of the first to show that the nutrient content of food resources can lead to changes in the nutrient content of consumers (Cross et al. 2003). In contrast to the flexible nutrient content in algae and detritus, consumers are theoretically and empirically less flexible in their body-nutrient content (Sterner and Elser 2002). Nevertheless, Cross et al. (2003) found that P content of some macroinvertebrates increased after 2 years of enrichment in the N + P experiment. The variation in invertebrate C:N:P was reduced by 30 to 40 percent in the enriched stream. Caddisflies (Trichoptera) as a group exhibited the

greatest change in body C:P compared to other insect orders. Changes in consumer body nutrient content of macroinvertebrates may affect growth and production of higher trophic levels by reducing the consumer-resource imbalance between prey and their predators.

Macroinvertebrate assemblage structure—

Policy and monitoring associated with assessing stream health in regards to the Clean Water Act currently and historically have focused on macroinvertebrate assemblage structure and biotic indices (e.g., Barbour et al. 1999, Rosenberg and Resh 1993). Although most of the studies of biological responses to nutrient enrichment experiments at CHL have focused on food web production and system-level C and nutrient fluxes, some aspects of macroinvertebrate assemblage structure have been shown to respond. Size structure of macroinvertebrates was affected by enrichment, which affected both instream predators (Davis et al. 2010a) as well as riparian spiders (Davis et al. 2011). Analysis of the N + P experiment macroinvertebrate data indicated very little response of traditional bioassessment metrics to nutrient enrichment until year 5 of additions when the treatment stream began to exhibit a significant departure from reference. These metrics are, however, coarse measures of assemblage structure. A more sensitive, detrended correspondence analysis, showed that shifts in community structure were occurring as a result of experimental enrichment and that this shift increased in subsequent years of enrichment (Rosemond, n.d.).

Vertebrate predator response—

Effects of nutrient enrichment were also found to affect vertebrate predators. Larval salamanders are the dominant vertebrate predator in streams at CHL and the only vertebrate predators in high-elevation streams, which are inaccessible to fish. Both the longer term N + P experiment and the N × P experiment have shown that nutrient enrichment stimulated larval salamander growth and growth rates (Bumpers et al. 2015, Johnson et al. 2006). Larval *Eurycea wilderae* growth rates increased in response to added N and P after only 9 months of enrichment, indicating higher trophic levels can be affected by nutrient enrichment relatively rapidly (Johnson et al. 2006). In the N × P experiment, similar but more comprehensive studies found that larval *Desmognathus quadramaculatus* growth rates increased up to 40 percent in both an enclosure study and a mark-recapture study of free-roaming larvae. Average body size of free-roaming *E. wilderae* larvae increased up to 66 percent owing to experimental nutrient addition. For both species, higher growth rates and larger body sizes were positively correlated with stream water P concentration, but not N concentration (Bumpers et al. 2015). Analyses of salamander food webs

in the N × P study found that *D. quadramaculatus* increased prey consumption, particularly of algivore prey relative to detritivores (Bumpers et al. 2017). Despite increased growth rates of *E. wilderae*, no significant diet response was detected in response to nutrient enrichment (Bumpers et al. 2017). The results of this study suggest that stream water P limited salamander growth in these systems. Together these studies indicate that nutrient effects can propagate through multiple trophic levels to affect vertebrate predators in largely P-limited streams such as those at CHL. Additionally, the positive nutrient effect on salamanders contrasted with the predaceous macroinvertebrate response, which showed no positive nutrient effect and became decoupled from prey. These results indicated that traits of individual predator species, such as life history and physiology, may strongly influence their response to nutrient enrichment.

Comparisons to other stream nutrient enrichment studies—

Few studies have been published of the responses of detritus-based stream systems to experimental nutrient additions with comparable spatial or temporal scales to the work done at CHL. Stelzer et al. (2003), for example, reported results of an ~9-week nutrient addition at HBEF. A long-term study by Slavik et al. (2004) investigated responses to 16 years of summer enrichment in the Kuparak River, an algal-based tundra river in Alaska. Energy flow in that river is dominated by instream algal primary production, which was initially stimulated by experimental P enrichment (Peterson et al. 1993). Macroinvertebrate responses were varied; several taxa responded positively via increased density or biomass, some taxa initially increased in density and then declined, and others were negatively affected by P enrichment (Peterson et al. 1993, Slavik et al. 2004). Growth rates of a vertebrate predator, adult arctic grayling (*Thymallus arcticus*), were stimulated by the addition of P (Slavik et al. 2004), which paralleled responses of larval salamanders in the CHL experiment. Unlike CHL, however, after 8 years of P enrichment, mosses replaced algae as the dominant primary producer, affecting insect abundances (Slavik et al. 2004), and a suite of ecosystem processes, including increased NH_4^+ uptake rates. A strength of the Kuparak study is that enrichment was studied long enough to capture complex and slowly developing responses to nutrient enrichment. Together with the work of Davis et al. (2010a) at CHL, these studies suggest that long-term responses of nutrients are difficult to predict from short-term experiments, highlighting the value of long-term (8+ years) experiments and monitoring. Additionally, the long-term enrichments at CHL and Kuparak River both revealed important biological consequences of nutrient enrichment, suggesting that approaches similar to those taken at these two sites have great potential to further understanding of biological and ecosystem responses to nutrient enrichment in other regions and stream types.

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

Stream studies at CHL are part of an integrated ecosystem study based on collaboration between the USFS and universities and, as a result, many other long-term monitoring datasets and shorter term research results can provide a rich context for interpreting results, including how these factors interact with N and P in CHL streams. For example, long-term climate data (e.g., temperature and precipitation), streamflow, and water chemistry data exists for several study watersheds within CHL. See “Availability of Publications and Data” above for more information.

Effects of terrestrial organic matter inputs—

Terrestrially derived organic matter plays a critical role in ecosystem structure and function of CHL streams. In 1993, a long-term, large-scale experiment was initiated at CHL in which leaf litter and wood inputs were excluded from a stream draining WS55 to investigate how terrestrial carbon inputs influence stream processes. A mesh canopy eliminated organic matter inputs into the stream for a 13-year period and results have been compared with a nearby reference stream. In 1996, all small wood (<10 cm diameter) was removed from the treatment stream, followed by large-wood removal in 1998. “Artificial wood,” consisting of polyvinyl chloride pipes, was subsequently added in 2000, and leaf litter in 2001. These experiments allowed a step-by-step assessment of the role of detrital organic matter in headwater stream processes (Wallace et al. 1997a, 1999, 2015). Leaf standing crops declined to near zero during year 1 of the exclusion and remained low until leaf litter was experimentally added back to the stream (Eggert et al. 2012). Phosphorus uptake in the treatment stream was greatly reduced following leaf exclusion relative to the reference stream (Webster et al. 2000) and remained very low during the wood-removal periods. Ammonium uptake rates were reduced as well, as indicated by increased uptake lengths. Nutrient concentrations in stream water were unaltered by leaf exclusion and were not significantly different from the reference streams (Tank et al. 1998). When leaves were added back into the stream, P uptake increased but was still below pretreatment levels. Only after 3 years of leaf addition did phosphorus uptake return to reference levels (Webster et al., n.d.). There was also evidence that biofilms were enhanced in the treatment stream during the litter-exclusion period, likely owing to reduced uptake on detrital resources (Tank and Webster 1998). Long-term measurements of the response of stream processes to leaf litter and wood manipulations unequivocally demonstrate the coupling of nutrient processes with detrital standing crops and the crucial role that organic matter plays in regulating headwater stream ecosystem structure and function.

Effects of dissolved organic carbon—

Dissolved organic carbon (DOC) is an important energy resource for microorganisms (e.g., Hall et al. 2000) and can control nutrient dynamics in streams (Bernhardt and Likens 2002). Brookshire et al. (2005) found that the addition of NO_3^- increased DOC uptake in Hugh White Creek in CHL. Moreover, demand for dissolved organic nitrogen (DON), such as urea, increased with DOC demand. This study demonstrated the tight coupling of N and C dynamics at CHL. DON demand is mediated by DOC demand, and DOC demand is mediated by dissolved inorganic N (DIN) availability, suggesting changes in either DOC or DIN can affect the other (Brookshire et al. 2005). These findings are consistent with those at HEBF (see chapter 3) and suggest that DOC dynamics have important consequences for stream nutrient dynamics and vice versa. Additionally, Wilcox et al. (2005) experimentally added labile DOC to a stream and found that bacterial densities and microbial respiration rates increased by threefold, likely affecting DIN dynamics. Chironomid growth rates also increased as a result of DOC addition.

Effects of climate—

Increases in temperature appear to increase N export and accelerate ecosystem N loss (Brookshire et al. 2011). Long-term trends and seasonality of NO_3^- concentrations in stream water at CHL are largely explained by microbial responses to temperature. The effect of warming may have a much greater effect on N export than atmospheric deposition, suggesting that in the southern Appalachians, the direct effect of climate change may increase NO_3^- export in stream water more than expected export from N deposition (Brookshire et al. 2011). However, the potential interactions between stream nutrient enrichment and climate warming has not been well studied.

Reference Watersheds

The CHL maintains eight designated reference study watersheds: WS 2 (12 ha), WS 14 (61 ha), WS 18 (13 ha), WS 27 (39 ha), WS 31 (34 ha), WS 32 (41 ha), WS 34 (33 ha), and WS 36 (49 ha), which have had minimal onsite human disturbance since they were established in 1943 or earlier (Swank and Crossley 1988). These watersheds have served as references in many studies at CHL and have been continuously monitored and studied as model systems for reference conditions in headwater streams of the southern Appalachians. However, larger scale environmental changes have likely affected these reference basins, including increased atmospheric N deposition (Brookshire et al. 2011) and increasing mean annual temperature (Laseter et al. 2012). Exotic organisms have also impinged upon the Coweeta basin as a result of exurbanization (Scott and Helfman 2001). Hemlock woolly adelgid (*Adelges tsugae*), an exotic insect pest, has caused tree mortality that may potentially affect

streamflow and stream chemistry at CHL (Brantley et al 2014), and cankerworm infestations partially defoliated WS 27 and WS 36 from 1972 to 1979 (Swank and Crossley 1988). Such exogenous perturbations are similar to what could be expected in other relatively undisturbed mountain watersheds in the region.

Baseline monitoring of stream water N (NO_3^- , NH_4^+) and P (soluble reactive phosphorus [SRP]) was initiated in CHL reference watersheds from 1971 to 1985, depending on the watershed, and has continued to the present. Monitoring of stream water total N and total P were added in 2005 and 2007, respectively (Miniat 2014).

A recent analysis of long-term trends in CHL stream chemistry (1972–2007) showed increasing NO_3^- and NH_4^+ concentrations in four reference watersheds of the CHL (Adams et al. 2014, Argerich et al. 2013). The increasing NO_3^- trend (mean increase of $0.2 \mu\text{g N/L/yr}$ for NO_3^- and $0.08 \mu\text{g N/L/yr}$ for NH_4^+) from minimally disturbed watersheds contrasts with the decreasing trend observed in the northern Appalachians where stream N concentrations are much greater than those found at CHL (see HEBF, chapter 3). The increasing trend in stream NO_3^- at CHL is likely partially driven by increasing atmospheric N deposition (Brookshire et al. 2011).

Cross-Site and Regional Studies

Nutrient dynamics—

Nutrient dynamics and transformations in CHL streams, such as uptake rates and denitrification rates, have been compared to streams in surrounding areas of the southeastern United States across a gradient of land use, and with other streams in North America (LINX collaborators 2014, Mulholland et al. 2008). These studies were part of a large continental-scale study of N dynamics in streams called the Lotic Intersite Nitrogen Experiments (LINX I and II). In these studies, isotopically labeled N was added to streams as ammonium (LINX I) or nitrate (LINX II). Compared to other LINX I study streams, Ball Creek at CHL exhibited very low rates of nitrification, accounting for only ~3 percent of NH_4^+ removal (Peterson et al. 2001). Webster et al. (2003) found that Ball Creek had very high NH_4^+ uptake velocity. These rates were higher than that of Walker Branch, a comparable but lower discharge forested headwater stream in Tennessee (Peterson et al. 2001). The high NH_3^+ uptake rates were likely due to seasonal differences between measurements. Ball Creek measurements were made during autumn and reflect heterotrophic demand from microbial colonization of newly fallen detritus; whereas Walker Branch measurements were made during spring (Mulholland et al. 2000). Additionally, Ball Creek measurements of NH_3^+ uptake rates in the LINX I studies were higher than that reported by Hall et al. (1998) for Hugh White Creek during the summer in Coweeta. Valett et al. (2008)

found strong and predictable seasonal patterns of N uptake in forested CHL streams (uptake lengths from 16 to 752 m). Demand was highest in the autumn, when allochthonous litter inputs peaked (uptake velocity four- to sevenfold higher than in other seasons). The autumn pulse of resources overwhelms thermal controls on N uptake, demonstrating the importance of organic matter in driving nutrient-uptake dynamics. Mulholland et al. (2008) compared NO_3^- removal dynamics in forest, urban, and agricultural streams across eight biomes, including three streams at CHL. They found that at low NO_3^- concentrations, biotic N removal is high and primarily occurs in small streams, such as those at CHL. Additionally, as NO_3^- increases, areal uptake rates of NO_3^- increase, but efficiency decreases.

Mulholland et al. (1997) compared P uptake between Hugh White Creek at CHL and Walker Branch in Tennessee. They found that the microbial community in Hugh White Creek exhibited high demand for P, as evidenced by rapid P uptake, and was likely a result of low ambient P concentrations and a greater supply of higher quality organic matter, compared to Walker Branch. The high rates of P uptake and short uptake lengths (~30 m) were similar to those reported by Webster et al. (1991) for other CHL streams. The hyporheic zone accounted for ~43 percent of P uptake in Hugh White Creek but was negligible in Walker Branch.

Regional studies of interacting factors with nutrients—

Forests at CHL are part of LTER-sponsored studies of human impacts along a gradient from forest to urban and agriculturally developed land in the Little Tennessee River watershed. These studies incorporate the effects of human disturbance and social dimensions of land use change on aquatic ecology (e.g., Brookshire et al. 2011, Cheever et al. 2012, Hagen et al. 2010). Nutrient concentrations, and the potential for greater primary production, increased with distance downstream from forested headwater streams (Gardiner et al. 2009, Scott et al. 2002). These regional studies have shown that co-occurring stressors from human disturbance created complex and variable ecosystem responses, such as mixed responses of litter breakdown to increased nutrients. Possible interacting factors include contaminants, altered bed substrate, altered temperature and flow regimes, and changes in macroinvertebrate assemblages. Hagen et al. (2006) found general increases in leaf litter breakdown rates along a gradient from forested (low-nutrient) to heavy agricultural (high-nutrient) streams in the Little Tennessee River basin near CHL. However, within the agricultural land use gradient, there were no significant relationships with nutrient concentrations. The lack of response to nutrients among agricultural streams was likely due to interacting factors related to land use, such as altered shredder abundance, temperature, or flow, that negated effects of increased nutrient availability.

Dose-Response Studies

Biological responses to a range of experimental additions of N and P to streams at CHL have been presented in the “Findings From Studies” section above and in table 14.1.

An additional nutrient-enrichment study at CHL was conducted in experimentally constructed streamside channels. This experiment used a greater range in concentrations of N and P than the whole-stream manipulations. Microbial breakdown of red maple and rhododendron leaf litter was tested across a gradient of 25 low to moderate N (32 to 550 $\mu\text{g N/L}$) and P (4 to 90 $\mu\text{g P/L}$) concentrations at N:P ratios ranging from 2 to 127. With enrichment, rates of breakdown of maple and rhododendron increased up to six- and twelvefold, respectively (Kominoski et al. 2015). Concentrations of both N and P were more closely related to breakdown rate than microbial biomass and respiration, which were more variable, but microbial biomass and respiration were also stimulated by N and P additions. This study suggests that concentrations of N and P that are common across the southeastern United States are stimulating microbial breakdown of leaf litter and, where both nutrients are high in streams, this effect is exacerbated (Kominoski et al. 2015).

Responses to Forest Management and Natural Disturbances

Studies at CHL evaluating the effects of various forestry practices were pivotal in the early development of best management practices (BMPs) (see Prud'homme and Greis 2002). Direct tests of BMPs at CHL have helped shape and revise those practices (e.g., Swift 1986). For example, stream responses to clearcutting of a watershed were studied in the late 1970s. Changes in Big Hurricane Branch, a second-order stream, following clearcutting of the entire watershed included increased streamflow, higher summer water temperatures, increased light, increased sediment load, and increased nutrient concentrations (Webster et al. 1983). Despite fertilizer application, NO_3^- levels did not increase significantly until 9 months after logging. This was largely attributed to biological uptake of nutrients before they reached the downstream weir where samples were taken. Peak NO_3^- concentrations were observed 1 year after logging, and increases in stream water concentration were attributed to increased N availability resulting from reduced forest vegetative uptake. During the next several years, NO_3^- concentrations decreased slightly owing to forest regrowth. However, concentrations then began increasing again, 12 years after cutting, peaking 20 years after treatment (Swank et al. 2001). These delayed N increases, long after treatment, were primarily due to insect infestation that killed a large stand of black locust (*Robinia pseudoacacia* L.), an N-fixing tree, and hydrologic variability. Decomposition of the dead trees contributed to NO_3^- enrichment

more than a decade after the initial logging treatment. This response shows complex interactions between logging and forest succession related to instream nutrient dynamics and highlights the importance of long-term monitoring for interpretation of stream recovery from disturbances (Swank et al. 2014). Export of other ions and solutes besides NO_3^- , as well as streamflow, approached pretreatment levels 4 to 6 years after treatment (Swank et al. 2014).

Natural disturbances can also increase stream nutrient concentrations and alter detrital dynamics. For example, insect defoliation elevated stream N concentrations ($770 \mu\text{g NO}_3^-/\text{L}$ in the disturbed stream vs. $6 \mu\text{g NO}_3^-/\text{L}$ in the reference stream) and increased leaf litter breakdown. (Meyer and Johnson 1983).

The effects of experimental near-stream rhododendron removal and naturally caused hurricane blowdown on nutrient export were compared for 3 years in WS 56. Nutrient losses from the soil water to the stream were significantly greater from the blowdown than from the rhododendron removal (Yeakley et al. 2003). The blowdown doubled hydrogen ions and increased NO_3^- in groundwater four-fold, and stream water NO_3^- concentration twofold, whereas the rhododendron removal increased NO_3^- concentration in streams 1.66-fold. Nutrient concentrations remained elevated 3 years following the blowdown (Yeakley et al. 2003). Chlorophyll *a* concentrations of instream primary producers increased downstream of both the rhododendron removal and blowdown areas and were related to increased light levels and nutrients (Eggert, n.d.).

Several studies at CHL show that riparian disturbances can create significant changes in DOC concentrations. Meyer and Tate (1983) found that DOC concentrations and export of DOC in a stream draining a clearcut watershed increased relative to a reference. Recent analysis 25 years after cutting indicated that DOC concentrations have since decreased, suggesting a net depletion of DOC sources as a result of clearcutting (Meyer et al. 2014). Meyer et al. (1998) found reduced DOC concentrations in the litter-exclusion project, which was primarily driven by reduced instream litter, illuminating the importance of leaf litter for DOC dynamics. Additionally, Yamashita et al. (2011) examined DOC quantity and quality in a reference stream compared to streams that underwent clearcutting and conversion to white pine (*Pinus strobus* L.) and found that concentrations of DOC in the disturbed watersheds were lower than in the undisturbed watershed. Collectively, these studies demonstrate how forest management and other human alterations to terrestrial habitats can affect stream water DOC. The tight coupling between DOC and nutrient dynamics suggests that perturbations that cause changes in DOC dynamics may alter nutrient dynamics and vice versa (e.g., Brookshire et al. 2005).

Reliability and Limitations of Findings

Results obtained at CHL generally represent southern Appalachian hardwood forest headwater streams that are relatively undisturbed or have received land use practices similar to those that have been implemented at CHL, such as timber harvesting and forest road construction. However, caution should be used when applying the findings of CHL to other stream systems. Validation studies may be needed in those areas to test how well CHL findings predict local conditions. Studies that use landscape-level gradients of nutrient concentrations owing to land use can provide insight into regional responses to nutrient enrichment (e.g., Evans-White et al. 2009). Finally, the long-term responses to enrichment in forested streams in the Southeast for periods longer than 8 years have not been studied and are not well understood.

Research Needs

From the perspective of the regional regulatory community, the highest priority research need that might be filled at CHL would be a better understanding of short-term vs. long-term nutrient enrichment effects and what thresholds of N and P enrichment produce biological responses. Filling this research need would be useful to water quality regulatory agencies for reducing scientific uncertainty in setting conservative nutrient criteria that consider effects of long-term chronic enrichment and avoid the negative consequences of nutrient enrichment in low-nutrient streams with high-quality water. Given biological responses to nutrients that were unexpected and manifested 3 years after enrichment at CHL (Davis et al. 2010a), it is critical to understand how streams in the southeastern United States will respond to chronic nutrient loading for periods longer than 8 years and how these long-term responses might differ from the 2- to 5-year studies that have been conducted.

Research conducted at CHL has shown that valuable insights into biological responses to stream nutrient enrichment can be obtained from stream-reach experimental nutrient additions, which are difficult to detect from landscape gradients because of confounding influences such as co-occurring additional stressors. A greater understanding of the long-term effects of nutrient enrichment could be gained at CHL by conducting long-term enrichment studies that compare and contrast acute (1-year) vs. chronic (10 years) nutrient enrichment to explore the relative influence of each, and, of particular interests to regulators, to identify what specific biological responses occur at threshold concentrations of N and P. Coweeta Hydrologic Laboratory could be used to conduct such studies because the relatively undisturbed streams would facilitate the isolation of nutrient effects. To capture long-term responses and feedbacks associated with N and P enrichment, experiments would need to be conducted for 8 years or longer. Studies should incorporate

both structure (assemblage) and functional (process) measures and investigation of the effects of co-limiting factors, such as light and temperature, in their design. Specifically, researchers would need to test a replicated gradient of low to moderate N and P concentrations over this long-term period and measure responses of chl *a*, terrestrially-derived C, and biological metrics currently used in nutrient criteria and bioassessment. An additional element could include alternating the dosage frequency across streams to compare responses to short- to long-term exposures to the same overall nutrient load. This design could be replicated on other relatively undisturbed streams at EFRs in other regions to broaden the applicability of results. Lastly, recovery trajectories would need to be monitored in order to fully understand how systems respond to and recover from chronic nutrient loading. This experimental framework would deliver valuable information over a long time period.

A number of secondary questions might also be addressed within this kind of experimental framework. Although answering them may be of lower priority for meeting regulators' science needs, they do address issues of importance to water quality criteria for nutrients, such as the frequency of nutrient delivery, but also illustrate the potential that this research approach might have to broaden the range of biological responses that could be considered in water quality standards for nutrients.

- How do changes in N and P loading interact with changes in C inputs and other stressors such as temperature and hydrology to affect carbon exports from streams?
- How resilient are streams to nutrient enrichment? Unexpected results and changes that occurred after 5 years of nutrient addition found by Slavik et al. (2004) and Davis et al. (2010a) highlight the need for more long-term experimental studies and comprehensive long-term monitoring of all biological components of stream ecosystems.
- What ecosystem characteristics confer resistance to nutrient effects? The interactions between detrital carbon and nutrients suggest that protecting or enhancing carbon inputs will promote nutrient uptake and reduce negative ecological consequences.
- How long does recovery from nutrient enrichment take and how do responses differ among the different levels of organization within the ecosystem, such as at the organismal, population, community, and whole-ecosystem levels?
- How does nutrient enrichment compare with responses to other commonly co-occurring stressors, such as sediment, riparian removal, and geomorphic alteration? Are there specific nutrient-related response signatures that can be used to diagnose nutrient stress among multiple stressors? Do other stressors amplify or mitigate nutrient enrichment?

Potential Utility to Water Quality Regulatory Agencies

Research from CHL on effects of N and P contribute valuable insights into the way detritus-based streams respond to enrichment, especially highlighting that long-term stream food web responses are difficult to predict from short-term enrichments, and that stream carbon dynamics interact in complex ways with nutrients. In general, research at CHL can offer valuable insight into the management of nutrients and highlight the profound effect that nutrients have on terrestrially derived carbon resources, which are critical for the support of stream food webs.

Long-term studies at the minimally disturbed catchments of CHL contribute valuable data on expected concentrations and long-term trends of nutrients in Appalachian streams in the southeastern United States, as well as data on natural variability of those concentrations that are crucial to informing regulatory agencies about magnitude and frequency components of numeric criteria. The streams at CHL also still represent the lower stress load and higher resistance end of response curves, and the research there is providing important information on ecological response thresholds at that end of the gradient. For example, responses to enrichment at CHL have been identified at low to moderate, yet realistic, levels of nutrient enrichment relative to those that occur across the southeastern United States, nationally, and globally (Scott et al. 2002, US EPA 2013, Woodward et al. 2012). Thus, meaningful consequences to ecosystem processes and stream biota are likely to occur in detritus-based forest streams in the Southeast that are experiencing increases in nutrients as low as ~200 µg/L DIN and ~15 to 20 µg/L SRP (Kominoski et al. 2015, Rosemond et al. 2015).

Research at CHL is providing much needed experimental nutrient stressor-response data on underappreciated detrital pathways by identifying ecological response thresholds that could be used by regulatory agencies as critical and powerful lines of evidence in developing defensible numeric nutrient criteria that include the effects of both N and P. There are many publications and datasets based on research conducted at CHL that help determine baseline nutrient conditions and changes that have occurred over the past 20+ years in these relatively unaffected streams. The two whole-stream enrichment studies at CHL provide comprehensive findings on the effects of nutrient enrichment in southeastern U.S. forest stream ecosystems. This research shows clear responses of detritus to increased N and P availability, highlighting the need to maintain detrital inputs into streams from streamside (riparian) forests in addition to managing nutrient concentrations.

Research at CHL has found that both N and P are important in driving the detrital responses. Additionally, the relationship of larval salamander growth and P concentration suggest that P enrichment, or N and P enrichment, may have a more pervasive effect on the entire ecosystem than N enrichment alone. Furthermore, the

altered food web pathways that included macroinvertebrate stream predators at CHL, and required more than 3 years of nutrient enrichment to emerge (Davis et al. 2010a), have highlighted the need for longer term enrichment studies for detection of complex biological responses.

Key points:

- Enrichment with N and P reduces leaf litter standing crops and increases export of particulate C, reducing the temporal and spatial availability of a critical resource for ecosystem processes and consumers.
- Carbon resources such as leaf litter are key in processes such as nutrient uptake.
- N and P enrichment affects nutrient content of algae and detritus, with effects that propagate through stream food webs to affect invertebrate and vertebrate predators.
- The effects of nutrients on food webs depend on species-specific traits such as body size, generation times, and habitat preferences, which together drive consumer responses to nutrients.
- The highest priority research gap to fill is to better understand long-term (8 + years) ecosystem responses to N and P enrichment, to identify the concentrations at which predictable changes in biological structure and function occur, and to identify the degree that concentrations can deviate from reference conditions before aquatic uses are negatively affected. Long-term enrichment studies that compare short-term (1 year) vs. long-term (8+ years) nutrient loading across gradients of nutrient concentrations would help close this information gap.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

There are currently no immediate concerns for stream health related to nutrients other than N and P, although changes in development or land use in the southern Appalachians might lead to future issues related to these nutrients.

Findings From Studies

The study watersheds at CHL are monitored for a suite of nutrients other than N and P, including Ca^{2+} , magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), Chloride (Cl^-), sulfate (SO_4^{2-}), and silicon dioxide (SiO_2). However, there are only a few experimental studies involving nutrients other than N and P. For example, Woodall and Wallace (1975) measured total standing stocks of Ca, Mg, and K in CHL streams.

Baseline monitoring of stream water chemistry indicates that Na^+ makes up about 43 percent of total cations followed by Ca^{2+} and Mg^{2+} (~23 percent each). Bicarbonate (HCO_3^-) makes up 74 percent of anions. Major differences can exist between low- and high-elevation streams, largely driven by differences in precipitation and streamflow. Notably, in high-elevation streams, concentrations of HCO_3^- are much lower, and SO_4^{2-} concentrations are much higher than in low-elevation streams (Swank 1988).

Reference Watersheds

Nutrients Cl^- , Na^+ , Ca^{2+} , K^+ , and Mg^{2+} have been monitored in reference watersheds W 2, W 18, W 27, and W 36 since 1971; in WS 14 since 1980, in WS 31 since 1984; and in WS 34 since 1985. Additionally, SO_4^{2-} and SiO_2 have been monitored since 1973 in WS 2, WS 14, WS 18, WS 26, and WS 36 (Miniat 2014).

Effects of Management and Natural Disturbances

Following conversion of a hardwoods watershed to white pine, retention of K^+ , Mg^{2+} , and Ca^{2+} increased by 50 to 70 percent (Swank and Vose 1994). This was largely attributed to greater primary production by white pines. A threefold increase in stream water sulfate was also observed. The pine forest was a more conservative system for base cations owing to lower discharge and retention of soil ions. After clearcutting Big Hurricane Branch watershed, stream water concentrations of dissolved ions Ca^{2+} , SO_4^{2-} , K^+ , Cl^- , Mg^{2+} , Na^+ , and SiO_2 all changed (Webster et al. 1983). Initial small increases in Ca^{2+} and K^+ were attributed to fertilizer applied to roads. Calcium concentrations and export continued to increase and peaked 3 years after logging. Calcium and K^+ concentrations remained elevated but stabilized in the long term. Golladay et al. (1992) evaluated the effects of high rainfall events on the export of nutrients in two watersheds that were clearcut and in two reference watersheds. They found no significant changes in the net export of dissolved Ca^{2+} or K^+ in response to disturbance, but generally disturbed streams exported more particulate Ca and K, although differences in underlying geology may have influenced these results.

Webster and Patten (1979) examined Ca^{2+} and K^+ dynamics in three streams, two of which were experimentally manipulated: one was maintained as an old field, one was planted in pine, and the third was a reference hardwood forest. Forest disturbances resulted in moderate changes to Ca^{2+} and K^+ dynamics. Additionally, Swank et al. (2014) summarized stream water chemistry responses to forest disturbances at CHL (see also Swank 1988) and reported generally modest changes in concentrations of nutrient other than N and P in response to forest disturbances at CHL.

Research Needs

Currently, there are no critical research needs regarding nutrients other than N and P at CHL.

Potential Utility to Water Quality Regulatory Agencies

Research at CHL on nutrients other than N and P has not been as high a priority. However, it has revealed that watershed disturbances experienced at CHL do lead to changes in several stream nutrients, but generally other nutrients are altered less than N and P. If future water quality issues related to nutrients other than N and P were to arise in the region, CHL monitoring datasets and research results might be of use to regulators addressing those issues.

Key points:

- Underlying bedrock geology may influence responses of nutrients such as Ca, Mg, and K.
- Forest management disturbances at CHL generally have effects on other nutrients that are smaller than the effects on N and P.

Overview and Synthesis

The body of research conducted at CHL can provide valuable insights for the regulatory community. Results of long-term monitoring and studies of streams in reference watersheds at CHL are available to provide numeric values from minimally disturbed landscapes for use in setting numeric criteria. Coweeta Hydrologic Laboratory and other EFRs are vital repositories of some of the last remaining minimally disturbed lands that are available for study and provide scientific data on stream conditions needed to help set reference-based numeric values that can serve as lines of evidence in developing regional numeric criteria. Moreover, nutrient datasets from the network of EFRs, including CHL, can help inform regulatory efforts to classify nutrient chemistry regionally and nationally by providing a basis for quantifying natural variability and trends in reference stream nutrient concentrations as well as incorporating time-varying data into the setting of nutrient criteria, especially patterns in the delivery of nutrients.

Variability in ecological responses to nutrients in streams is, in part, a function of co-occurring stressors and co-limiting factors that often obscure or antagonize nutrient stress and make it difficult to identify response thresholds. Stream-scale nutrient enrichment experiments, such as those conducted at CHL, are critical for understanding the variety of ecological responses to nutrient enrichment and to identifying response thresholds, as well as disentangling the effects of co-occurring

stressors and co-limiting factors, as was evidenced by the citation of CHL research in national stressor-response guidance and numeric nutrient setting efforts (e.g., US EPA 2010). Results of CHL research have strong potential to improve the clarity of ecological response models and to help develop more defensible numeric criteria for protecting stream ecosystems.

Numeric nutrient effects have largely focused on primary producer response pathways and have insufficiently considered the effects of enrichment on detrital pathways, as was demonstrated by an almost complete absence of attention given to detrital response pathways in guidance (US EPA 2010). An underlying assumption has been that small, headwater systems take up and process nutrients and thereby protect downstream waters. Results from experimental research at CHL provide scientific evidence that this benefit from headwaters systems also entails a cost of altered ecological structure and function, including significantly decreased nutrient uptake efficiency, and changes in organic matter dynamics, secondary production, and macroinvertebrate assemblage composition. There is a need to explore more thoroughly such complex biological responses to stream nutrients and how they manifest over larger spatial and temporal scales.

Lastly, there is an ongoing national debate among states on the relative role of N vs. P limitation and, despite pervasive evidence of colimitation (Elser et al. 2007), some continue to argue for management of a single nutrient, primarily P. There is, therefore, a current need for improved scientific understanding of effects of N enrichment on stream ecosystems and of the interactions of N and P in co-limited water bodies. The water quality regulatory community would benefit from science produced at CHL and other EFRs that helped to resolve this question.

Key points:

1. Potential practical uses by the regulatory community of science products from CHL:
 - CHL data provide robust characterization of baseline nutrient concentrations and natural variability in nutrient concentrations for southern Appalachian forested streams.
 - CHL nutrient addition experiments have produced a comprehensive understanding of N and P effects on detritus-based headwater streams based on stream-scale nutrient manipulations.
 - The nutrient addition experiments suggest the need to maintain or restore detrital inputs into streams in addition to setting numeric criteria for N and P.
 - Both N and P are important in driving ecosystem responses. The effects of nutrient addition on CHL streams occurred at low-to-moderate

concentrations of N and P relative to what is occurring across most of the southeastern United States and the nation.

2. Important scientific gaps for regulators that might be filled at CHL:
 - Increase understanding of how responses differ between chronic and short-term nutrient loading and how far N and P concentrations can increase before designated aquatic uses are negatively affected. Additionally, a comprehensive understanding of short- vs. long-term responses will require understanding how nutrient loading interacts with multiple stressors (e.g., riparian disturbance, other contaminants, altered geomorphology), as commonly occurs in streams in human-modified landscapes.
3. How priority science gaps might be filled at CHL:
 - Filling the identified information gaps would require specifically designed nutrient addition experiments that test a gradient of N and P concentrations (e.g., low/low, low/high, high/low, and high/high) over multiple generation times of organisms. Aquatic life uses should be monitored to determine negative biological responses to provide regulators with scientific evidence on response thresholds.
 - Recovery trajectories of streams could also be measured to better estimate how streams might respond to restoration by nutrient reduction management.

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Chapter 15: Ecoregion 8.5.3 Southern Coastal Plain: Santee Experimental Forest, South Carolina

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Introduction

This chapter synthesizes environmental monitoring and studies performed at Santee Experimental Forest (SEF) that are relevant to water quality within the lower coastal plain (LCP) of the southeastern United States. The SEF lies within the Carolina Flatwoods section of the LCP (Griffith et al. 2002) where forested wetlands strongly influence water quality through hydrological and biogeochemical processes and provide important ecosystem services.

Site Description

The SEF consists of 2469 ha of federal land dedicated to research, demonstration trials, and long-term monitoring. SEF (lat. 33° 08' 15" N, long. 79° 49' 0" W) is located within the Francis Marion National Forest near Huger, South Carolina, 50 km northwest of Charleston, South Carolina (fig. 15.1). Terrain consists of broad flats and bottomlands, with elevation ranging from 0 to 21 m above sea level. Forest vegetation is dominated by loblolly pine (*Pinus taeda* L.), oaks (*Quercus* spp.), and other hardwoods, and longleaf pine (*P. palustris* Mill.) typical of the flatwoods forest (Harms et al. 1998). About 70 percent of the SEF is within the habitat management area for the red-cockaded woodpecker (*Picoides borealis*), which is listed as endangered under the Endangered Species Act (16 USC 1531 et seq.). The SEF research watersheds are nontidal headwaters of Huger Creek, a freshwater tidal creek, within the Cooper River Estuary that opens to the Atlantic Ocean.

The SEF has low-gradient, black-water streams that drain the flatwoods landscape. These streams have beds of unconsolidated sediments with textures ranging from clay to sand and broad floodplains. Most streams have considerable woody debris and leaf litter within the channel, derived primarily from riparian vegetation. Bottomland deciduous hardwood trees dominate the riparian zone, producing a closed canopy except during the leaf-off season from mid-November until mid-March.

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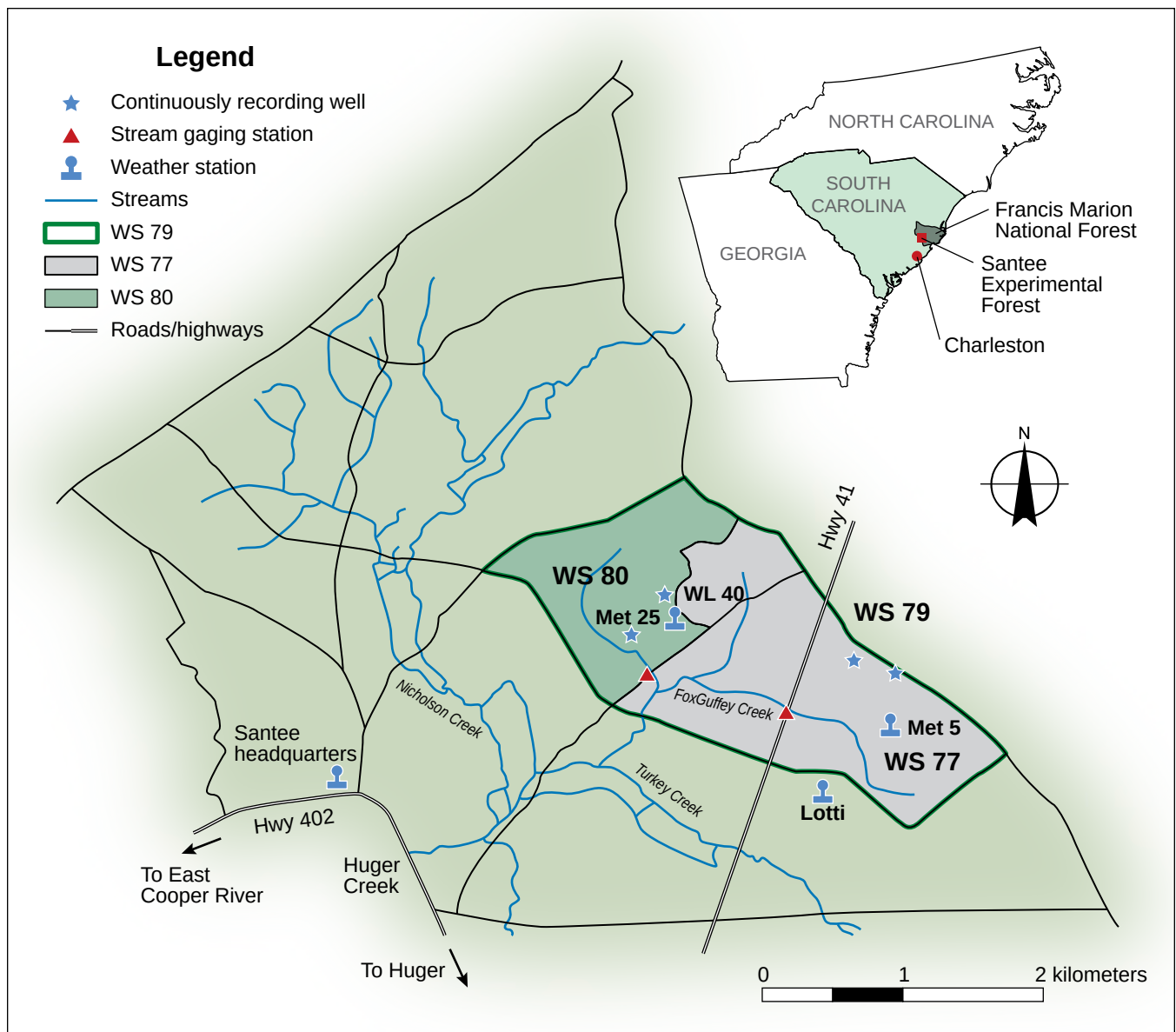


Figure 15.1—Santee Experimental Forest near Huger, South Carolina. Three gaged watersheds (WS 77 and WS 80 inside the larger WS 79) are indicated. Locations of streamflow monitoring stations (triangles) and meteorological stations (stars) are also shown (from Harder et al. 2007).

Climate is subtropical, with an average annual temperature of 18.3 °C and average annual precipitation of 1370 mm (Dai et al. 2013). The forest was heavily affected by Hurricane Hugo in 1989 (Hook et al. 1991), and its current vegetation consists of relatively young stands that are vigorously regrowing in the aftermath of this tropical storm.

Soils in SEF are predominantly Aquic Alfisols and Ultisols (USDA SCS 1980), primarily somewhat-poorly to poorly drained sandy loams with clayey subsoils. These soils have high surface-water retention capacity and low permeability, producing slow surface-water drainage (USDA SCS 1980).

Research History

The land comprising the SEF has a long history of agricultural use and timber extraction (Smith 2012). The SEF was established in 1937 by the U.S. Forest Service (USFS) with a mission of silvicultural research, environmental monitoring, demonstration, and educational activities in support of sustainable forest management practices. Gaged watersheds were installed during the mid-1960s to study the effects of forest management practices on surface water hydrology and water quality. The two first-order watersheds, which average 28 percent wetlands, are characteristic of the LCP (Sun et al. 2000). The monitoring of watersheds began in November 1963 on nested first- and second-order streams, and an adjacent third-order stream was discontinued in May 1982 and resumed from November 1989 to the present. Watershed hydrology, weather, and water quality data are available at the SEF website (USDA FS 2017).

Program of Research

The focus of research in SEF watersheds has been the effects of silvicultural practices and natural disturbances on ecosystem processes, hydrometeorological and biogeochemical processes, flooding patterns, water budgets, and wetland hydrological regimes (Amatya et al. 2006, 2007, 2015). An initial goal was to establish paired watersheds (reference and treatment) to assess the effects of silvicultural practices. Early research investigated water budgets and runoff dynamics (Young and Klaiwitter 1968). This was followed by research that assessed the effects of prescribed fire on soil and stream water chemistry (Richter et al. 1983).

Over the past 20 years, the greater Charleston metropolitan area, including land surrounding SEF, has experienced rapid growth in population and urban development. Datasets from SEF can represent reference conditions for the forested LCP that have experienced natural disturbances or disturbances associated with forest management treatments; accordingly, these watersheds provide a useful baseline for assessing impacts of development in other watersheds within the coastal landscape. Datasets for SEF watersheds include repeated vegetation surveys, extensive records of land use and detailed LiDAR data, all of which give context for interpreting results from experimental studies conducted in the watersheds.

Monitoring and experimentation—

The meteorological dataset for the overall SEF site included daily measurements of precipitation and air temperature that began in 1946. Two full meteorological stations are maintained on the forest. Monitoring of streamflow, precipitation, soil moisture, and water table elevation began in 1963 in WS 77, a first-order watershed. Watershed WS 79, associated with a second-order stream, and watershed WS 78, associated with a third-order stream, were subsequently established (Young and

Klaiwitter 1968). WS80 was established as a first-order reference watershed in 1968. WS 77 was salvage logged in 1989 following Hurricane Hugo. Post Hurricane Hugo, additional forest management treatments were implemented on WS 77, including mastication or mechanical mowing of understory vegetation, thinning, and periodic prescribed fire. Vegetation in WS 77 currently consists of loblolly pine, longleaf pine, and, bottomland hardwoods within the riparian zones.

Instream water quality monitoring—

Weekly instream water quality samples were collected by grab sampling at the watershed outlets for the periods 1976–1982, 1989–1994; and, continuously since 2003 on a flow-proportional basis at the outlets of WS 77, WS 79, and WS 80. Sampling and laboratory protocols are described by Amatya et al. (2007).

Atmospheric deposition and ambient air pollution monitoring—

Wet and dry atmospheric deposition rates and surface-level ambient ozone concentrations have been monitored at SEF since 2008, and status of data is shown in table 15.1. The atmospheric deposition protocols correspond with the National Atmospheric Deposition Program NADP (NADP 2019), although SEF is not a formal member of the NADP.

Availability of publications and data—

Hydrometeorological, instream water quality and atmospheric deposition data and associated metadata may be accessed from the SEF website (USDA FS 2017). Long-term daily climate and streamflow datasets, formatted for comparison with like datasets from numerous other experimental forest and range (EFR) and long-term ecological research (LTER) sites, can be downloaded from the ClimDB/HydroDB website (LTER Network 2013).

Biological Responses to Stream Nutrients N and P

Issues of Concern

In the southeastern United States, elevated nitrogen (N) and phosphorus (P) can cause undesirable growth of aquatic plants. Excessive inputs of these nutrients can impair beneficial uses of surface waters through eutrophication and reduced dissolved oxygen (DO). The predominant sources that result in N and P enrichment in waterbodies in this region are nonpoint source discharges of N and P, from agricultural and urban lands, and atmospheric deposition of N compounds. Nutrient loading from the LCP streams to coastal estuaries and near-shore waters is a threat to important fish and shellfish resources and has the potential to negatively affect commercial and recreational fisheries, as well as tourism, that depend on these resources (Lapointe and Bedford 2007).

Table 15.1—Status of hydrologic (rain and streamflow), stream water chemistry, and air quality variables being measured on reference (WS 80) and treatment (WS 77) watersheds at Santee experimental watersheds before and after Hurricane Hugo in 1989

Variable	Years before Hurricane Hugo	Years after Hurricane Hugo	Management
Rain	1969–1981	1989–94; 1996–1999; 2003–present	WS 77 for post-Hugo, mechanical mowing of understory, thinning, and periodic prescribed fire. Loblolly pine, longleaf pine, and, bottomland hardwoods in riparian zones dominate WS 77. Plants were left to naturally regenerate on WS 80 for post-Hugo. Loblolly pine and hardwoods dominate WS 80.
Flow	1969–1981	1989–1994; 1996–1999; 2003–present	
NH ₄ ⁺ -N, NO ₃ ⁻ -N, TKN, and TN	1976–1981	1989–1994; 2006–present No TKN on both watersheds	
PO ₄ ³⁻ and TP	1976–1981 (PO ₄ ³⁻ only on WS 77 and WS 80)	1989–1994; 2006–present (TP only on WS 77 and WS 80)	
DOC		2004–present	
Ca ²⁺ , Mg ²⁺ , K ⁺ , and Na ⁺	1977–1980	1990–1994; 2003–present (WS 77); 2004–present (WS 80)	
Cl ⁻ and SO ₄ ⁻²	1977–1980	1990–1994; 2003–present (WS 77) 2004–present (WS 80) No SO ₄ on both watersheds (2003–2007)	
pH	1976–1982	1989–1994; 2003–present	
Dissolved oxygen		2006–present	
Conductivity		2006–present	
Temperature		2006–present	
Salinity		2006–present	
Wet and dry atmospheric deposition of N and P		2008–present	

Variables: NH₄⁺-N = ammonium-nitrogen, NO₃⁻-N = nitrate-nitrogen, TKN = total Kjeldahl nitrogen, TN = total nitrogen, PO₄³⁻ = phosphate, TP = total phosphorus, DOC = dissolved organic carbon, Ca²⁺ = calcium, Mg²⁺ = magnesium, K⁺ = potassium, Na⁺ = sodium, Cl⁻ = chloride, SO₄⁻² = sulfate, N = nitrogen, and P = phosphorus.

Findings From Studies

Instream N and P—

Stream water at the outlets of watersheds WS 77, WS 80, and WS 79 have been monitored for nitrate (NO_3^-)-N, ammonium (NH_4^+)-N, total N (TN), phosphate (PO_4^{3-})-P, and total P (TP) for intermittent periods from 1976 to 1994 and continuously since 2003. Wet and dry atmospheric deposition of these same nutrients has been monitored at SEF since 2008.

Binkley (2001) reported that stream water NO_3^- -N concentrations on WS 80 were very low, averaging 0.017 mg NO_3^- -N/L, with highest values in winter and early spring. NH_4^+ -N concentrations averaged 0.045 mg/L, more than double those of NO_3^- -N. Ammonium concentrations declined with increased streamflow, but NO_3^- -N concentrations did not change as flow increased. Dissolved organic nitrogen (DON) averaged ~1 mg/L, which was tenfold higher than dissolved inorganic nitrogen (DIN). Phosphate-P (PO_4^{3-} -P) concentrations averaged 0.028 mg/L and declined slightly with increased flow. These nutrient concentrations were consistent with other black water streams draining southeastern forested watersheds dominated by conifers (Chescheir et al. 2003).

Instream biological surveys—

Biological monitoring in SEF streams has consisted primarily of fish surveys. Following Hurricane Hugo in 1989, Hansbarger and Dean (1994) surveyed fish in Fox Gully Creek draining the treatment watershed (WS 77), and it was resampled in 2002, 2003, 2004, and 2006 (Krause and Roghair 2010). The number of fish species captured has differed widely, with 10 species reported in 1993, 4 in 2003, and 3 in 2006. Except for the banded killifish (*Fundulus diaphanous* Lesueur), recorded fish species were native to the Santee-Cooper Drainage. The trophic composition of the fish assemblage in Fox Gully Creek remained unchanged from 1993 to 2006. Insectivores dominated the community, which indicated that invertebrate food sources were probably stable. One species of freshwater mussel, *Elliptio complanata*, was also reported in Fox Gully Creek (Krause and Roghair 2010). Concurrent with the fish surveys, DO, temperature, hardness, pH, and alkalinity were also measured (Krause and Roghair 2010). Survey data are available from USFS Southern Research Station, Center for Aquatic Technology Transfer. Additional biological monitoring has been done in streams of the surrounding Francis Marion National Forest (Hansbarger and Dean 1994), and macroinvertebrates were sampled in SEF streams in 2013, collaboratively with South Carolina Department of Health and Environmental Control (SCDHEC), although results are not yet published. New work, begun in 2016, is studying the response of aquatic invertebrate communities to prescribed fire, comparing communities within WS 80 and WS 77 streams.

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

Streamflow—

The annual water budgets of the first-order watersheds were described by Young and Klaiwitter (1968) and Harder et al. (2007), and the effects of climate variability on hydrologic processes and conditions on the SEF were characterized by Dai et al. (2013). WS 77 and WS 80 are highly responsive to rainfall, and the ratio of runoff to precipitation is dependent on antecedent moisture conditions (Amatya et al. 2006, Jayakaran et al. 2014). This hydrologic response is similar to that of WS 78, an adjacent third-order watershed (Amatya et al. 2015, La Torre Torres et al. 2011). Annual stream outflow from WS 80, as a fraction of annual precipitation averaged 9 percent and ranged from 5 percent in 1981 to 43 percent in 1997. On WS 77, runoff as a fraction of precipitation averaged 25 percent, and ranged from 9 percent in 2004 to 44 percent in 1991. Such wide ranges resulted from shallow water table dynamics that are driven by evapotranspiration and precipitation. As a result, the contributions to streamflow from shallow surface runoff and subsurface drainage are highly variable (Epps et al. 2013) and influence stream export of dissolved and particulate nutrients.

Other stream water quality parameters that may influence biological responses, including pH, temperature, conductivity, and DO, have been measured intermittently in both the reference (WS 80) and treatment (WS 77) watersheds since the mid-1970s.

Dose -Response Studies

Dose-response studies have not been conducted at SEF.

Reference Watershed

WS 80 was established as a first-order reference watershed in 1968, and since then has been protected from onsite human disturbance. WS 80 is 160 ha (206 ha before 2001) and drained by a single stream. Surface elevations within this watershed range from 3.7 to 10 m with 0 to 3 percent slopes (Harder et al. 2007). Portions of the bottomlands were used for rice cultivation from the late 1700s to the mid-1800s, while the uplands were used for livestock and production of timber and forest products (Smith 2012). Following incorporation into the Francis Marion National Forest in 1933, vegetation on previously disturbed areas was not managed but was allowed to naturally regenerate. The mixed-conifer and hardwood stands that developed are considered typical for this landscape (Czwartacki and Trettin 2013).

Studies of WS 80 provide rare scientific evidence of the response to severe hurricane disturbance and subsequent ecological recovery of an LCP forest and stream without onsite human disturbance. Before Hurricane Hugo, the vegetation consisted

of mixed stands of oak and loblolly pine. In 1989, Hurricane Hugo destroyed over 80 percent of the forest canopy (Hook et al. 1991). Post-Hugo, the watershed's forest was allowed to regenerate naturally; fallen and dead standing trees were left in place, and no timber was removed. In the decades following Hugo, the forest vegetation regenerated, with mixed hardwoods and pine predominating, and streams were allowed to respond without human intervention.

Results of stream water monitoring of N and P on this reference watershed since 1976 are reported under the heading "Findings From Studies: Stream Water N and P." The response of N and P in this stream to Hurricane Hugo are described below in the section "Response to Management Practices and Natural Disturbances." For more detailed descriptions of this reference watershed and associated studies, see Amatya et al. (2005), Harder et al. (2007), and Epps et al. (2013).

Cross-Site and Regional Studies

Stream water N and P—

Amatya et al. (2009) studied the relationship between streamflow and water quality for the third-order Turkey Creek watershed (WS 78), a forested watershed extending beyond the SEF into the Francis Marion National Forest. Stream water quality data in this basin is available for 2006–2009, for the nutrients NO_3^- -N+ nitrite (NO_2^-)-N, NH_4^+ -N, TN, and TP. Concentrations were within the ranges reported for the other SEF watersheds (Amatya et al. 2007) and other basins with similar land use within the LCP, except NH_4^+ -N, which was slightly higher in Turkey Creek than in the SEF WS 77 and WS 80 streams. Muwamba et al. (2016) reported that, similar to WS 79 and WS 80, organic-N dominated N chemistry in Turkey Creek, with very low levels of inorganic N.

Watersheds on the SEF were part of the nationwide assessment of streams that examined patterns of temporal variation in stream water chemistry (Binkley 2001). SEF was among eight EFRs that were detailed in the assessment, which included over 300 streams. The low DIN and PO_4^{3-} and high DON concentrations observed in SEF streams were consistent with other southeastern forested watersheds dominated by conifers. Data on wet and dry atmospheric deposition of NO_3^- -N, NH_4^+ -N, TN, and PO_4^{3-} -P, collected at SEF, have not been used by NADP in regional or national deposition syntheses nor to map pollutant loading.

Responses to Management Practices and Natural Disturbances

Effects of prescribed burning and thinning—

Prescribed fire is a common silvicultural practice in pine-dominated flatwood forests in the LCP. This treatment is used to reduce potential risk of severe wildland

fire by lowering accumulation of biomass fuel on the forest floor, and for restoring critical habitat for longleaf pine and endangered red-cockaded woodpecker (*Leucotopicus borealis* Vieillot). Understory hardwoods compete significantly for soil moisture in upland pine forests of the mid-south (Harrington and Edwards 1999); consequently, control of understory vegetation with prescribed fire or mastication can result in increased streamflow (Amatya et al. 2006).

A treatment of winter burning of understory and pine litter was implemented on 20 percent of WS 77 each year for 5 successive years from 1976 to 1981. No significant changes were found in water quality, water yield, or soil properties compared to the untreated reference watershed (Richter et al. 1983). Mean annual stream TN and TP loads showed no substantial response, compared to reference, from either the annual partial burning during the 1976–1981 period, nor from a thinning in 2006 followed by burning in 2007 and 2009. During the treatment years 2006–2011, TP exports from both the treatment and reference basins were almost equal at 0.02 ± 0.02 kg/ha/yr. A before-and-after comparison for the treatment watershed (WS 77), however, revealed decreases in total cumulative monthly TN loads of 0.58 kg/ha and decreases in total cumulative monthly TP loads of 0.02 kg/ha compared to the 2004 to 2006 pretreatment period, although only the result for TP was significant ($\alpha = 0.05$).

Effects of Hurricane Hugo—

Data from Wilson et al. (2006) indicated a significant increase in average stream water outflow from WS 80 for 3 years following Hurricane Hugo, the most severe natural disturbance since SEF was established. Annual exports of N and P from the unmanaged WS 80 were significantly higher in the post-Hugo period compared to the pre-Hugo period. The largest increase (39 percent) was for NO_3^- -N followed by 21 percent for total Kjeldahl N, organic N (ON), and TN and 6 percent for PO_4^{3-} (Wilson et al. 2006). The managed watershed (WS 77) had post-Hugo increases in stream N and P that were similar to the reference. Wilson et al. (2006) concluded that forest disturbance by Hurricane Hugo increased nutrient exports from the SEF watersheds during the first 5 years after the hurricane primarily as a result of increases in streamflow, but the authors noted that the increased exports were above a very low prehurricane baseline. The likely mechanism explaining these findings was that hurricane damage to vegetation reduced both evapotranspiration and vegetative uptake of nutrients, which increased runoff (Jayakaran et al. 2014) and nutrient exports. Other studies have reported similar increased outflows of water and nutrients from other coastal forested watersheds damaged by Atlantic hurricanes.

Comparisons of pre- and post-Hugo periods—

Measured stream water concentrations of NO_3^- -N and NH_4^+ -N were very low both before and after Hugo for both WS 77 and WS 80, with ON the dominant form of N in both watersheds (fig. 15.2). During the post-Hugo period, ON was significantly ($\alpha = 0.05$) lower (0.35 ± 0.08 mg/L) than in the pre-Hugo period (0.71 ± 0.42 mg/L) in study watershed WS 77, but not in reference watershed WS 80. On the other hand, NH_4^+ -N and DIN were significantly higher ($\alpha = 0.05$) for the post-Hugo period compared to the pre-Hugo period, but only in watershed WS 80. Slightly higher ON values observed in the WS 77 watershed post-Hugo were not significantly different when compared to values from the pre-Hugo period. Stream water nutrient concentrations in WS 80 showed that export of TN and PO_4^{3-} had returned to pre-Hugo mean levels 16 to 21 years after the hurricane disturbance (fig. 15.3). The TN and PO_4^{3-} loads in both watersheds during the post-Hugo regeneration period were found to be substantially lower than those of the pre-Hugo period,

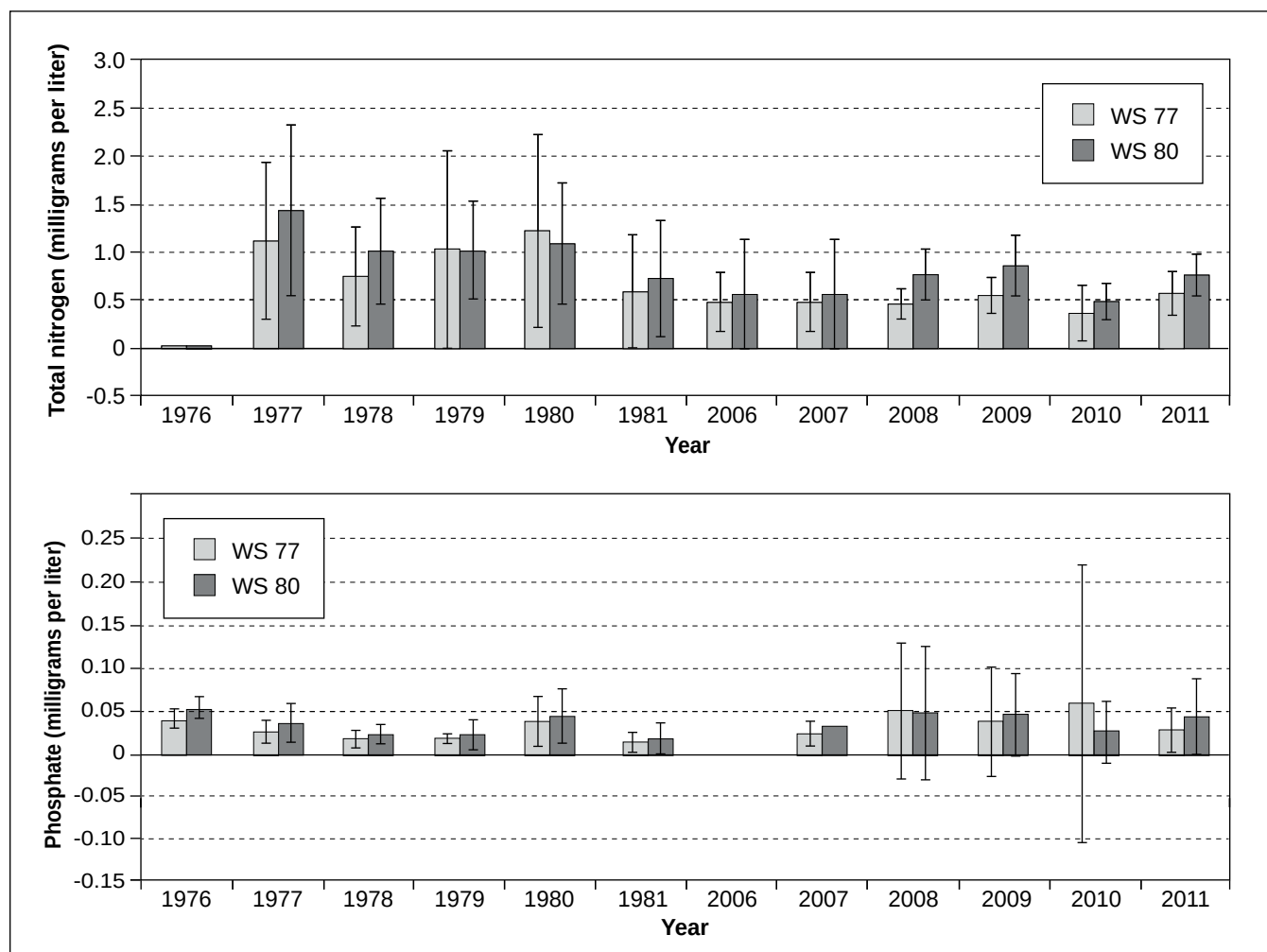


Figure 15.2—Mean and standard deviation (vertical bar) of annual concentrations of total nitrogen (top) and phosphate (PO_4^{3-} -P) (bottom) for the WS 77 (treatment) and WS 80 (reference) watersheds for pre- and post-Hugo periods.

although in WS 77, only TN was significantly different ($\alpha = 0.05$). Decreased loads during the regeneration period were probably the result of reduced streamflow in both watersheds reported by Jayakaran et al. (2014), who cited the return to pre-Hugo streamflow levels as evidence that the hydrologic cycles, and possibly the cycles of N and P, in this coastal forest were resilient even after the severe disruption of Hurricane Hugo.

Effects of dry and wet years on nutrient export—

Droughts are recurring natural disturbances that affect nutrient export from SEF watersheds. During prolonged dry periods of low rainfall in the years 2007 and 2011 (Amatya et al. 2015), exports of TN and TP were much smaller than during the other years of the post-Hugo period (figs. 15.3 and 15.4). Both annual average flow and TN concentrations were lower in 2007, whereas only average annual flow was lower in 2011. During the relatively wet year of 2008, the opposite was true; TN export was significantly higher ($\alpha = 0.05$) than during the other years of the

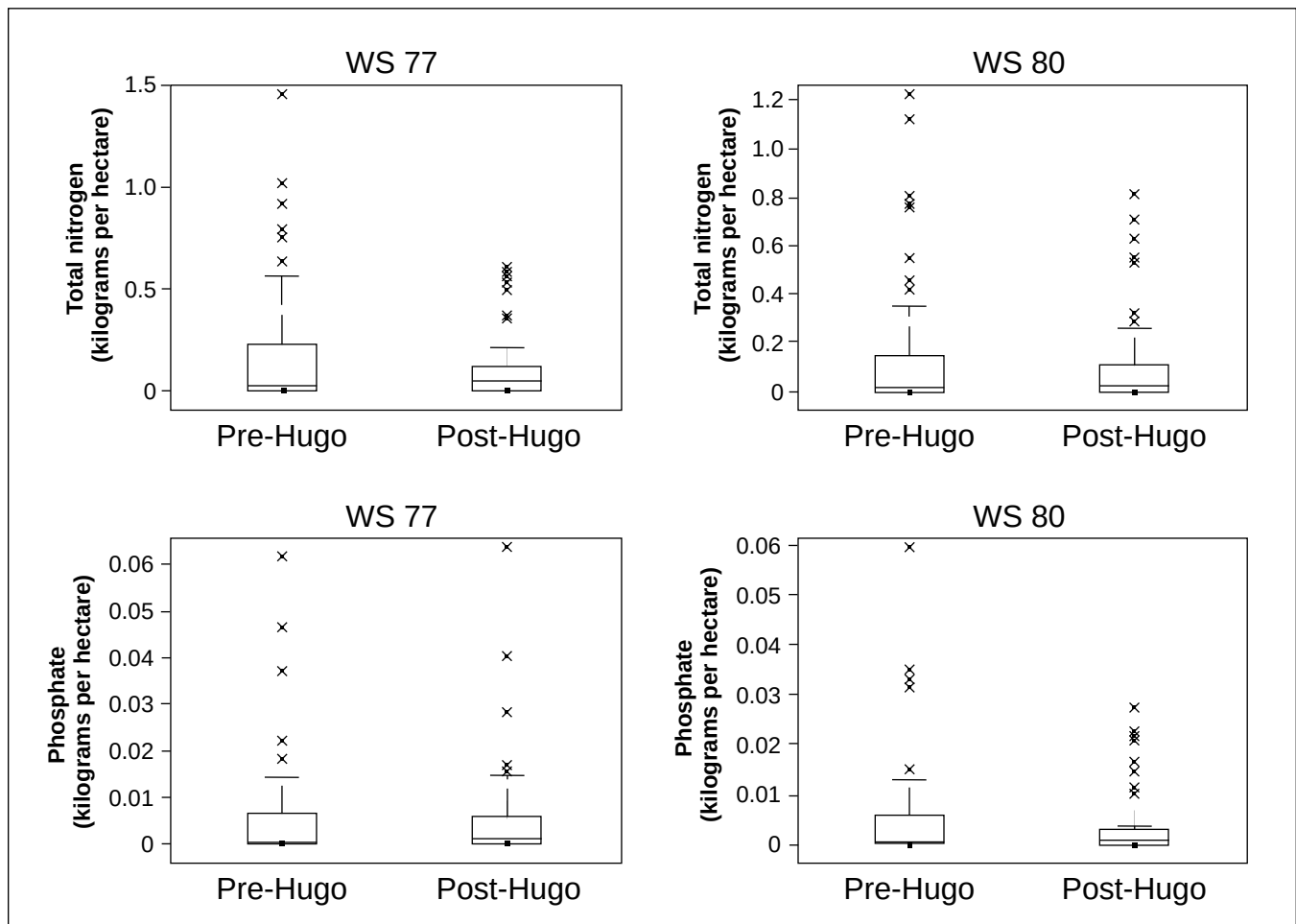


Figure 15.3—Distribution of calculated monthly loads of total nitrogen and phosphate-phosphorus for watershed (WS) 77 (treatment) and WS 80 (reference) watersheds for the pre- and post-Hugo periods.

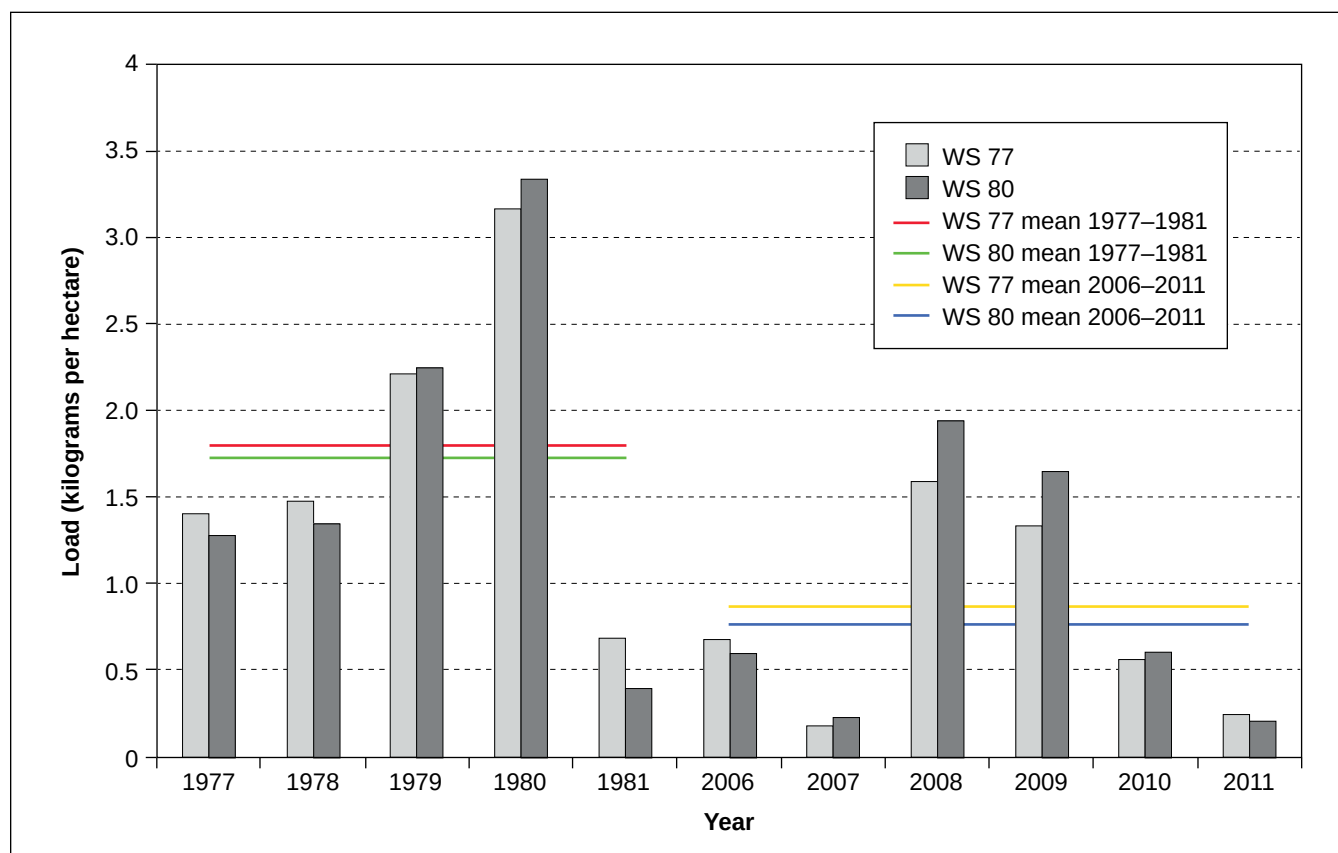


Figure 15.4—Calculated annual total nitrogen loads for WS 77 (treatment) and WS 80 (reference) watersheds for the post-Hugo (2006–2011) period. The horizontal lines are the mean annual values.

post-Hugo period. Similarly, TP loads were much lower in the dry years, 2007 and 2011, while higher TP loads occurred in the wetter year, 2008, in both watersheds, WS 77 and WS 80 (fig. 15.5). However, lower TP concentrations in dry year than the wet year were significantly different only in the treatment watershed and only in the dry year 2007, but not during 2011, nor in the reference watershed in either year. Thus on an annual basis, hydrology, largely driven by rainfall, seemed to have the largest influence on export of TN and TP from SEF forests to downstream ecosystems; although, in some dry years, decreased stream water concentrations of those nutrients also played a role.

Reliability and Limitations of Findings

The SEF findings are representative of LCP forests on the southeastern Atlantic seaboard. When a high degree of accuracy is required or where land use differs from SEF, validation monitoring or studies might be considered to test how well data and results from SEF predict local conditions.

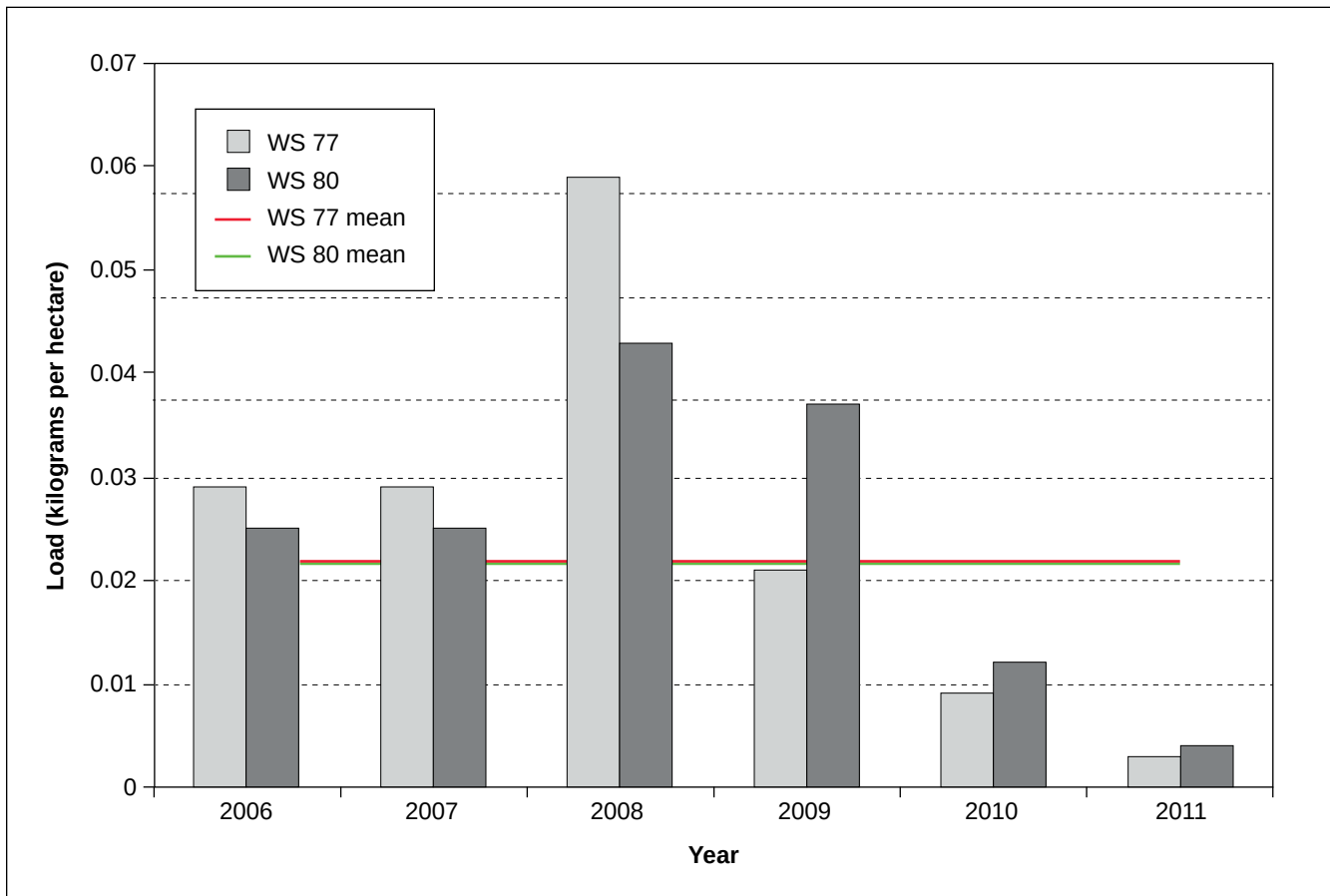


Figure 15.5—Calculated annual total phosphorus loads for watershed (WS) 77 (treatment) and WS 80 (reference) watersheds for the post-Hugo (2006–2011) period. The horizontal line is the mean annual value for the entire period.

Research Needs

From the perspective of state water quality regulators, the highest priority research need related to N and P that might be addressed at SEF is, What salient features of the aquatic biology of LCP streams are useful indicators of reference condition, and could these indicators be used to detect, characterize, and quantify a biological response across a gradient of nutrient enrichment? Filling this research need would help regulatory agencies develop data-driven bioassessment tools for headwater streams in this region of the state. Filling this need at SEF would require initiating and regularly repeating stream biological surveys in the SEF reference watershed that would include algae, macrophytes, macroinvertebrates, and fish. Concurrently, monitoring of channel geomorphology, as well as other instream ecological processes, such as whole-stream metabolism, leaf litter breakdown, and nutrient spiraling would also need to be performed. In addition, biological response thresholds to stream nutrient enrichment would need to be investigated, either by comparing the biological assemblages in SEF reference streams with streams across

a gradient of nutrient loading, or by conducting nutrient enrichment experiments. Such experiments would consist of monitoring biological responses to additions of varying concentrations of N and P, separately and in combination, to selected stream reaches or to artificial stream microcosms.

The following questions were formulated by state water quality regulators to identify useful, but lower priority, research needs that could be investigated at SEF:

- What are the relationships between multiple stressors in headwater streams, including nutrient loading, and other factors, such as temperature, and drought, and what are their combined effects on important instream ecological processes, such as whole-stream metabolism, leaf litter breakdown, and nutrient spiraling?
- How do seasonal variations in DO and organic matter influence a stream's biological assemblage; and how might a better understanding of seasonal effects be used to adjust biological monitoring and assessment protocols to produce more representative and meaningful results?
- What are the salient characteristics of streams in this region of the state (e.g., biological, geomorphological, and hydrological) that differ predictably across a gradient of hydrologic permanence ranging from ephemeral (consisting of surface storm water runoff only) to perennial flows (consisting of surface runoff and groundwater); and, might these be used to rapidly classify streams in the field?
- How do instream biological assemblages, and the physical features and processes that sustain them in freshwater tidal streams downstream of SEF, respond to variations in nutrient loading of N and P from headwater streams such as those in SEF?

Potential Utility to Water Quality Regulatory Agencies

Existing long-term datasets from SEF, including streamflow and stream water nutrient concentrations and fluxes, on both reference and managed or treatment watersheds, along with data on nutrient inputs from atmospheric deposition have the potential to be very useful for SCDHEC's efforts to establish numeric nutrient criteria for estuaries, rivers, and streams. For example, long-term data from the SEF reference watershed were used in comprehensive analyses of flow and water quality in the Charleston Harbor (TetraTech 2008), providing valuable context for natural, background loading from headwaters to the estuary. The reference data were also used in revisions to total maximum daily loads (TMDLs) completed recently for the Charleston Harbor (Lu et al. 2005), and the Cooper and Ashley Rivers (Cantrell 2013), as required by the federal Clean Water Act (CWA) section 303(d). SEF

stream data provide baselines that may be used by regulators when setting numeric nutrient criteria, and when developing protocols and practices for monitoring, assessing, and preventing excessive nutrient and other pollutant inputs that come from the urbanizing landscape.

There has been a long-standing and sustained recognition of the importance of headwater streams (US EPA 2014, Vannote et al. 1980), including those with only seasonal or ephemeral flow, to the overall health of watersheds and to large downstream receiving waters, including rivers and estuaries. The SEF site is well suited for research on the contributions of perennial, intermittent, and ephemeral headwater streams within the LCP to the chemical, physical, and biological integrity of downstream waters, especially freshwater tidal streams and estuary waters.

Overall, the SEF site has great potential to provide valuable scientific information to regulatory decisionmakers, natural resource managers, and others. Its strategic location, the public availability of its data, its existing long-term record of water quality and streamflow, and its connectivity to sensitive downstream estuaries enhance its potential usefulness for regulators. Regulators might draw upon SEF research results for developing science-based approaches to setting standards; conducting monitoring and assessment; evaluating permit applications, proposed impacts, and compensatory mitigation; and developing and implementing TMDLs throughout this region of South Carolina. For example, data on DO and carbon might be useful for developing allowable discharge limits that are protective of the estuary. Similarly, information on background nutrient loading could be used to provide the foundation for TMDLs for the LCP. Long-term environmental datasets, such as streamflow and meteorological records, might also provide a useful context for interpreting the extensive data SCDHEC has collected from conducting monitoring of benthic macroinvertebrate assemblages in streams in the vicinity of SEF (fig. 15.6).

Headwater streams have been monitored at SEF in a reference watershed reflecting minimal human disturbance over a long period. These datasets could be useful to SCDHEC in reviewing and approving compensatory mitigation plans for stream restoration activities under CWA Section 401 Water Quality Certifications. For example, long-term datasets from the SEF reference watershed might be used to develop an understanding of, and describe reference condition for, streams and wetlands in this region of the state. This would be helpful for setting appropriate expectations for results from stream restoration activities, including calculating credits appropriately, and setting appropriate ecological performance standards, both interim and final, and monitoring requirements.

In 2010, SCDHEC began developing extensive hydrology and water quality datasets to provide a basis for assessments and models. Data and published

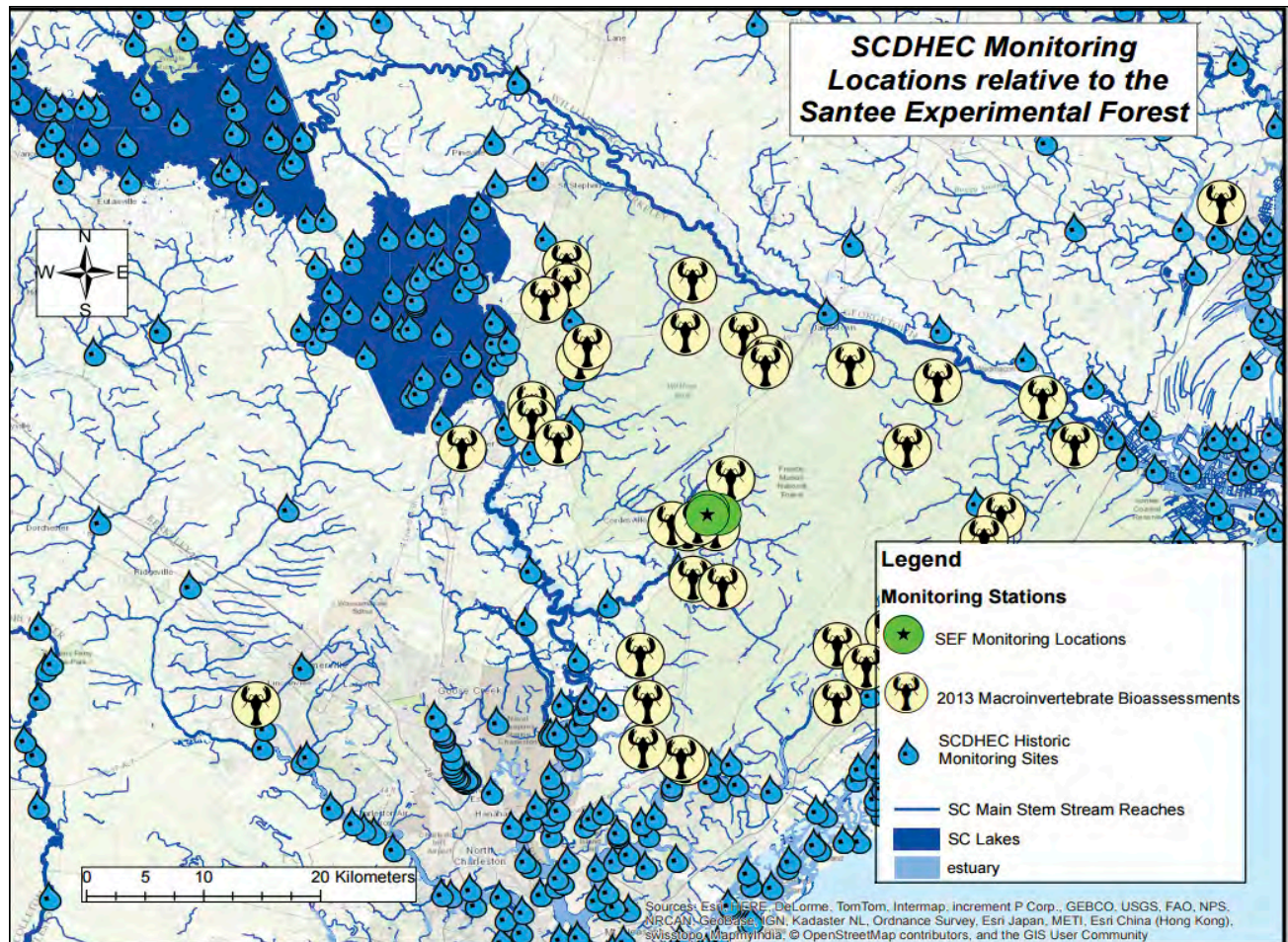


Figure 15.6—South Carolina Department of Health and Environmental Control (SCDHEC) biological monitoring stations for benthic macroinvertebrate communities in the vicinity of Santee Experimental Forest (SEF) in eastern South Carolina (SC).

research from SEF provide a scientific basis for regulators to use in developing models of water quality in LCP forests. Such data and models might be useful to regulators for accounting for outputs from managed and unmanaged forested lands when developing water quality standards and TMDLs for this region, and as part of developing numeric criteria for estuaries in South Carolina (Wilson 2010). Similarly, existing datasets from SEF that include repeated vegetation surveys, extensive records of land use, and detailed LiDAR data can augment water quality and streamflow data and might be useful to water quality regulators for assessing the effectiveness of riparian buffers in reducing nutrient loading, maintaining and improving downstream waters, and in developing recommendations for minimum buffer requirements.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

There are currently no pressing concerns in the region related to direct effects of nutrients other than N and P on water quality.

Mercury—

A potential issue related to the nutrient sulfur may be indicated by elevated methyl mercury (MeHg) levels that have been found in tissue samples from fish from LCP streams within the Francis Marion National Forest and from the East Fork of the Cooper River, downstream of SEF (Pelva and Hansen 2003). A neurotoxin that accumulates in aquatic food chains, MeHg reaches high tissue levels in apex predator food fish, posing a risk to human health (Bradley et al. 2012). Methyl mercury is the most biologically active and toxic form of Hg found in the environment and was found to be enhanced by increased ambient levels of SO_4^{2-} in wetlands at the Marcell Experimental Forest (chapter 2) (Jeremiason et al. 2006). Prescribed fire in upland areas may also affect Hg cycling, perhaps by altering ambient SO_4^{2-} , and can potentially increase Hg mobilization and transport out of watersheds subject to this management practice (Woodruff and Cannon 2010).

Findings From Studies

Stream water quality monitoring in WS 77, WS 79, and WS 80 has included calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), sulfate (SO_4^{2-}), chloride (Cl^-), and bromide (Br^-) for intermittent periods from 1976 to 1994, and continuously since 2003. Concentrations of these ions were similar to those in other LCP black water streams. These ions have also been monitored in wet and dry atmospheric deposition at SEF from 2008 to present.

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

Environmental factors studied at SEF that were identified earlier as affecting responses to N and P would also affect responses to nutrients other than N and P. These factors include parameters such as streamflow, pH, temperature, conductivity, and DO.

Reference Watershed

Stream water quality at the outlet from reference WS 80 has been monitored for Ca^{2+} , Mg^{2+} , K^+ , Na^+ , SO_4^{2-} , Cl^- , and Br^- since 1976. The response of these nutrients to Hurricane Hugo in this reference stream are reported in the section “Response to Management and Natural Disturbances” below.

Cross-Site and Regional Studies

SEF has not been included in cross-site studies related to nutrients other than N and P. Data on wet and dry atmospheric deposition of nutrients other than N and P, collected at SEF, have not been included in NADP regional studies, nor in national syntheses or mapping of deposition.

Responses to Management and Natural Disturbances

Stream fluxes of basic cations, Ca^{2+} and Na^+ , did not respond to management practices, and Richter (1980) reported no water quality impacts to waters near burned pine forest. Comparing dissolved organic carbon (DOC) concentrations for the years 2012 and 2013, greater concentrations were recorded from reference WS 80 than from treatment WS 77, likely as a result of periodic burning in WS 77.

In the aftermath of Hurricane Hugo, annual mean concentrations of Ca^{2+} , Mg^{2+} , K^+ , Na^+ , and SO_4^{2-} showed an increase for both WS 77 and WS 80 for the 1990 to 1994 period compared to the pre-Hugo period from 1977 to 1981 (table 15.2). Subsequently, stream water concentrations of these ions were lower during the 2008 to 2013 period, after forest vegetation had recovered from hurricane damage (Jayakaran et al. 2014), compared to the immediate post-hurricane period of 1990 to 1993. Maximum post-Hugo concentrations of these nutrients in WS 77 and WS 80 streams are compared to concentrations in the pre-Hugo period in table 15.2. Nutrient concentrations increased in both streams after Hugo during 1990–1994 (table 15.2), presumably as a result of decay of the large input of dead plant materials,

Table 15.2—Maximum stream water concentrations of Ca^{2+} , Mg^{2+} , K^+ , Na^+ , and SO_4^{2-} during pre- and post-Hurricane Hugo periods in WS 77 (treatment) and WS 80 (reference).

Period	Watershed	Calcium (Ca^{2+})	Magnesium (Mg^{2+})	Potassium (K^+)	Sodium (Na^+)	Sulfate (SO_4^{2-})
mg/L						
Pre-Hugo (1977–80)	WS 77	7.7	1.5	2.7	8.0	5.9
Post-Hugo (1990–94)	WS 77	13.1	2.6	8.1	13.5	10.5
Pre-Hugo (1977–80)	WS 80	21.6	3.9	3.5	8.2	8.7
Post-Hugo (1990–94)	WS 80	40.7	3.0	5.2	14.3	17.4

WS = watershed.

and suppression of vegetative nutrient uptake. The sole exception was Mg^{2+} , which decreased after Hugo in the WS 80. The ratio of post-Hugo to pre-Hugo maximum concentrations in stream water for reference watershed WS 80 was 1.9 for Ca^{2+} , 0.77 for Mg^{2+} , 1.5 for K^+ , 1.7 for Na^+ , and 2.0 for SO_4^{2-} .

Reliability and Limitations of Findings

Stream-related datasets and research results related to nutrients other than N and P from SEF apply to other LCP forested watersheds that have had land use histories similar to SEF. Where a high degree of accuracy is required or land use histories differ from SEF, validation monitoring or studies should be considered to test how well data or results from SEF represent local conditions.

Research Needs

The highest priority research need for the regulatory community, that might be addressed at SEF, related to nutrients other than N or P, was identified as, Do SO_4^{2-} enrichment scenarios or typical prescribed fire treatments lead to increased production of MeHg and increased bioaccumulation of MeHg within LCP wetland and stream food chains? Answering this question is critically important to regional regulatory agencies because fish consumption advisories related to MeHg are common in coastal waters. Science on the sources and pathways of Hg contamination will be useful for developing more effective regulations to protect the public from this health risk. Answering this question at SEF would require conducting studies that include prescribed fire treatments and measuring Hg and MeHg in stream water, in benthic sediments, and in food chains, including fish tissue samples from fish species most likely to be consumed by the public. Effects of SO_4^{2-} enrichment on MeHg production in SEF wetlands would also need to be investigated experimentally in microcosms and field plots. Continued monitoring of SO_4^{2-} levels in SEF streams and atmospheric deposition would provide status and trends of ambient SO_4^{2-} , which may be a factor in MeHg production in streams.

Other research needs of interest to the water quality regulatory community, but of lower priority, include how prescribed fire may affect production of organic compounds that may interfere with drinking water purification treatments (Chow et al. 2007), and how nutrients contained in suspended sediments might contribute to total nutrient fluxes from LCP headwater catchments.

Potential Utility to Water Quality Regulatory Agencies

Water quality regulatory agencies might be able to use existing long-term datasets from monitoring of nutrients other than N and P in stream water and from atmospheric deposition at SEF for practical regulatory purposes such as develop-

ing TMDLs and better storm water regulation. Research results on effects of prescribed fire, and effects of tropical storms on stream nutrients other than N and P might also be of immediate use to regulatory agencies for practical applications. For example, they might use them for assessing the impacts of extreme precipitation events on loading, for planning and permitting allowable withdrawals and discharges, and for considering the potential effects of altered flow regimes on nutrient transport.

Because SEF is set aside to remain undeveloped, it might serve as a valuable reference system and study site to assess how forests serve to buffer effects of urban development on coastal streams and stream ecosystems services, such as providing clean drinking water, mitigating floods, and contributing to productive aquatic habitat.

Key points:

- Nutrients other than N and P have been monitored in stream water and from atmospheric deposition at SEF.
- Disturbance from Hurricane Hugo temporarily increased stream water concentrations and fluxes of most nutrients other than N and P, but disturbance from the management practice of prescribed burns had little effect on the concentrations of those nutrients in stream water.
- The research need of highest priority to the regulatory community related to nutrients other than N and P that might be filled at SEF is investigating the effects of sulfate enrichment and prescribed fire treatments on production of MeHg in LCP wetlands and its accumulation in aquatic food chains.
- Existing SEF datasets and research results on nutrients other than N and P might be used by regulators for practical purposes such as incorporating effects of forest management and severe hurricanes into development of water quality criteria and TMDL models.

Overview and Synthesis

The location of SEF on the LCP, directly above the stream-to-estuary interface, enhances the value of this study site for water quality regulatory agencies. Research and monitoring from SEF may be useful for addressing regional water quality issues such as effects of prescribed fire, hurricane damage, and rapid urbanization on wetlands and streams in LCP forests that provide important inputs of freshwater and nutrients to coastal estuaries. SEF can provide science-based information about reference conditions in LCP streams that might be useful for developing standards or thresholds for both hydrology and nutrients. The body of scientific work at SEF

has focused primarily on hydrology and water quality monitoring. Investigations of aquatic biology have mostly consisted of fish surveys. Future studies, including monitoring and assessing the biological response to water quality factors including nutrient levels and fluxes could build on that foundation.

Research needs that might be filled at SEF that are of highest priority to the regulatory community were identified as developing science-based biological indicators of reference stream conditions, thresholds of biological response to N and P enrichment, and the effects of sulfate enrichment and prescribed burns on wetland MeHg production and its accumulation in aquatic food chains. Future work to fill these needs will benefit regulatory agencies by providing a scientific basis for developing sensitive bioassessment tools for headwater streams in the LCP, and for developing water quality regulations that better protect public health against the environmental hazard of MeHg contamination in fish. Cooperation between water quality regulatory agencies and the USFS on research at SEF has the potential to produce results that will both serve regulatory purposes and advance scientific understanding of the structure and function of these ecosystems.

Key points:

- SEF is an important source of long-term datasets providing scientific findings for understanding conditions in headwater streams that drain forested wetlands in the LCP, and that provide direct inputs to coastal estuaries via the stream network.
- SEF's carefully protected reference watershed provides a good, reliable baseline for conditions of minimal human disturbance that may be useful in developing criteria, TMDL modeling, and permitting.
- While fish surveys have been conducted in SEF streams, less is known about other biological assemblages such as benthic macroinvertebrates and algae.
- Effects on stream conditions of management practices, such as thinning and prescribed burns, and effects of natural disturbances, such as hurricanes, have been extensively investigated in SEF watersheds.
- Research needs that might be filled at SEF of highest priority for the regulatory community were identified as developing biological indicators of reference stream condition, developing an understanding of biological thresholds of response to N and P enrichment, and developing an understanding of the effects of sulfate enrichment and prescribed burns on wetland MeHg production and its accumulation in aquatic food chains.

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Chapter 16: Ecoregion 11.1.1 California Coastal Sage, Chaparral, and Oak Woodlands: San Dimas Experimental Forest, California

Peter M. Wohlgemuth, Philip J. Riggan, and Shirley A. Birosik¹

Introduction

This chapter is a review and synthesis of research conducted in and adjacent to the San Dimas Experimental Forest (SDEF) on stream nutrients and biological responses to stream nutrients. It is intended to inform national and regional water quality regulatory agencies, such as the U.S. Environmental Protection Agency, the California Regional Water Quality Control Boards, and the California Department of Forestry and Fire Protection, about existing results of relevant scientific studies that are available at SDEF, and to identify future field and synthetic research of potential use to regulatory agencies that might be conducted at SDEF.

Site Description

SDEF is located in a front range of the San Gabriel Mountains, 45 km northeast of Los Angeles in southern California (fig. 16.1). SDEF (lat. 34.182° N, long. 117.764° W) is 7000 ha in area, ranges in elevation from 450 to 1675 m, and has very steep hillslopes averaging 65 to 70 percent and stream channel gradients averaging 10 to 15 percent (Dunn et al. 1988). Vegetation on SDEF is predominantly mixed chaparral with chamise (*Adenostoma fasciculatum* Hook. & Arn.), scrub oak (*Quercus berberidifolia* Liebm.), and various ceanothus species (*Ceanothus* spp). Scattered trees grow in the upper riparian zones, including California live oak (*Q. agrifolia* Née) and California laurel (*Umbellularia californica* (Hook. & Arn.) Nutt.), while the lower reaches support fairly dense riparian woodlands of sycamore (*Platanus occidentalis* L.), willow (*Baccharis salicifolia* (Ruiz & Pav.) Pers. Liebm.), various oaks, and white alder (*Alnus rhombifolia* Nutt.). Some pine-oak forest occurs at higher elevations, especially on north-facing aspects, including canyon live oak (*Q. chrysolepis* Liebm.), big-cone Douglas-fir (*Pseudotsuga macrocarpa* (Vasey) Mayr), sugar pine (*Pinus lambertiana* Douglas), and remnant ponderosa pine (*P. ponderosa* Lawson & C. Lawson). Major disturbance events have included stand-replacing wildfires that burned large areas within SDEF in 1919, 1960, and 2002.

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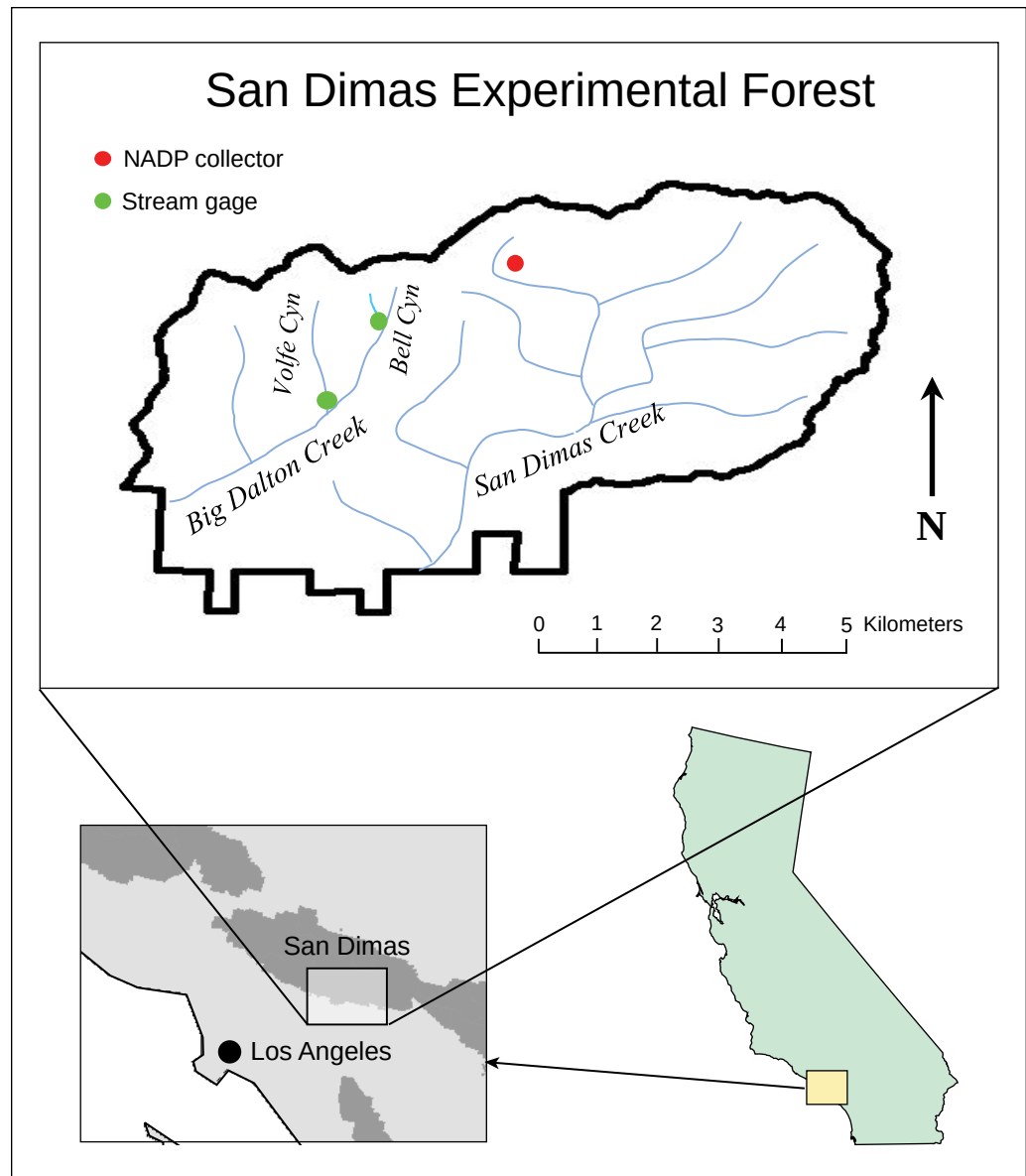


Figure 16.1—The San Dimas Experimental Forest showing major streams, sites of stream gages, and the National Atmospheric Deposition Program (NADP) monitoring station.

SDEF headwater catchments contain ephemeral first- and second-order streams with little riparian zone development. Lower elevation fourth- and fifth-order streams are intermittent, with year-round surface flow in wet years, but periods of no flow in dry years. The structure of streams in SDEF consists primarily of steep, bedrock channels with a shallow alluvial lag. Well-defined pools and riffles are not usually apparent in SDEF streams.

The streams in SDEF are part of the San Gabriel River contributing area and are useful for regional comparisons because they have had relatively few anthropogenic impacts. For example, SDEF streams have received minimal recreational

visitation and thus reflect an absence of associated streamside roads or extensive trail systems that can affect natural stream structure and water quality. In addition, SDEF channels have not been hydromodified, a common practice in this region, to stabilize channels and control flow characteristics by lining streambeds with concrete and armoring streambanks. Because of their relatively natural condition, SDEF streams can provide a baseline for assessing human impacts to streams elsewhere in the region.

The SDEF has a Mediterranean-type climate with cool, wet winters and hot, dry summers. The mean annual temperature is 14 °C, with summer maxima frequently exceeding 38 °C but winter minima seldom below -4 °C. Average annual precipitation is 715 mm but has varied greatly with extremes ranging from 250 to 1800 mm/yr over an 80-year record. Precipitation is dominated by rain that falls primarily between December and March (Dunn et al. 1988).

SDEF has shallow, azonal, coarse-textured upland soils of low fertility. These soils are classified as loamy, mixed, thermic, shallow, Typic Xerorthents that developed from tectonically fractured igneous and metamorphic bedrock (Riggan et al. 1985).

Research History

The SDEF was established in 1934 on federal lands of the Angeles National Forest (ANF), and all land use has been thoroughly documented since that time. Since 2014, the SDEF has been part of the San Gabriel Mountains National Monument. The original mission of SDEF was to study the water cycle in semiarid upland terrain and determine if any extra water could be harvested to support agriculture and domestic water supply in the valleys below (Robinson 1980). Research has followed a number of themes at SDEF. Hydrology studies have included developing stream instrumentation (Wilm et al. 1938), paired watershed comparisons (Crouse 1961), and lysimeter studies (Patric 1961). Soils and slope stability research have investigated surface sediment transport (Wohlgemuth 2015), shallow soil slips (Rice et al. 1969), and large mass movements (Morton and Streitz 1969).

Since the 1950s, research at SDEF has investigated the effects of wildland fire and management practices on water quantity. Studies of the effects of fire have included soil water repellency (DeBano 1981), streamflow (Krammes and Rice 1963), sediment yield (Wohlgemuth 2015), and erosion control (Rice et al. 1965). Chaparral ecology and physiology have documented postfire vegetation development (Horton and Kraebel 1955), species composition shifts (Hanes 1971), rooting depths (Hellmers et al. 1955), biomass accumulation (Riggan et al. 1988), plant water relations (Patric 1974), and litter decomposition (Kittredge 1955). Wildlife studies have investigated insects (Ikeda 1985), small mammals (Larson 1985), and Neotropical birds (Rechel et al. 2000). Vegetation management and

experimental manipulations have included type conversion of chaparral to grass and prescribed burning.

Long-term, continuous monitoring at SDEF includes measurements of air temperature, windspeed and direction, relative humidity, solar radiation, precipitation, and stream discharge. Stream water quality monitoring began in the early 1980s but was suspended in 2002 when siltation from a wildfire precluded stream discharge measurements. Both stream runoff and water quality monitoring were scheduled to resume in 2012, but prolonged and unprecedented regional drought resulted in no measurable flow. Discharge and water quality measurements finally resumed in 2017, with the return of normal storm patterns. Short-term studies have documented rainfall interception, infiltration, evapotranspiration, and hillslope overland flow.

Availability of publications and data—

Data are available in archives housed at SDEF, some of which have been summarized in published papers (see references in Dunn et al. 1988). Chemical loading by wet atmospheric deposition has been monitored since 1986 as part of the National Atmospheric Deposition Program (NADP), and these data are available online (NADP 2019a). Streamflow data, most of which have been converted to digital records, and water quality monitoring records are housed at the U.S. Forest Service (USFS), Pacific Southwest Research Station in Riverside, California. For more details about the history and scientific studies on SDEF, see Robinson (1980), Dunn et al. (1988), or USDA FS (2017).

Biological Responses to Stream Nutrients N and P

Issues of Concern

A major concern for regulators and water suppliers is that the high levels of nitrate (NO_3^-) in southern California surface waters may pollute the groundwater sources that help supply Los Angeles and surrounding cities. In upland forests such as SDEF, the main source of nitrates is from high rates of atmospheric deposition of nitrogen (N), primarily generated by air pollution from automobile emissions. These air pollutants are trapped in an inversion layer that is pushed against the inland mountains by onshore airflows from the Pacific Ocean. Surface water NO_3^- levels in southern California reflect a gradient of air pollution loading that was measured across the region (Fenn and Poth 1999, Fenn et al. 2008, Riggan et al. 1985). Atmospheric deposition of N compounds in headwater mountains, including SDEF, is thought to be the driver of surface water levels of NO_3^- that approach the federal drinking water standard of 10.0 mg NO_3^- -N/L that was set to protect human health. Following wildland fire, stream water NO_3^- levels in this region sometimes exceed

this standard (Riggan et al. 1994). However, it is difficult to assess the downstream impact of this headwater NO_3^- source on regional aquifers because valley lands also have legacy sources of NO_3^- from past intensive agriculture and N fertilizer application (Main San Gabriel Basin Watermaster 2013). A related concern is impacts on benthic invertebrates and fish from overfertilization and eutrophication of surface streams and acidification of upland ecosystems. Phosphorous (P) is of lesser regional concern, although it is suspected of contributing to the eutrophication of stream water after wildland fires.

Hydromodification is another regional concern. Naturally flowing streams and their associated riparian habitats and floodplains mitigate effects of nutrient loading by a variety of biological, chemical, and physical processes that reduce amounts of nutrients, sediments, and organic material delivered to downstream waters (US EPA 2015). These ameliorating effects are impaired in hydromodified streams, allowing more nutrients to remain in the water column, increasing downstream eutrophication and altering benthic invertebrate communities.

Findings From Studies

Overall nutrient conditions—

Annual yields as high as 10.0 kg NO_3^- -N/ha/yr and short-term stream water NO_3^- concentrations as high as 7.0 mg NO_3^- -N/L have been measured at SDEF watersheds with undisturbed native vegetation (Riggan et al. 1985). These NO_3^- values are some of the highest for undisturbed lands in the United States and up to 1,000 times greater than have been measured in streams in southern California with lower atmospheric deposition loads (Riggan et al. 1985). Dry deposition is a greater contributor of N than wet deposition in the Mediterranean climate of SDEF (Fenn et al. 2012, Padgett et al. 2014). Substantial amounts of NO_3^- and other N compounds are dry deposited onto shrub leaf surfaces and washed off by subsequent rainfall. Wash-off of N in throughfall, which is precipitation collected beneath the vegetation canopy, is greatest during late-summer and early-autumn events, when small storms are interspersed with periods of elevated air pollution (Riggan et al. 1985).

Measurements in the early 1980s indicate that the average combined transfer of inorganic N, including oxides of nitrogen and ammonium, from the air to the soil was 23.3 kg N/ha/yr, of which 8.2 kg N/ha/yr was from wet deposition (Riggan et al. 1985). More recent analyses of long-term monitoring data indicated that wet deposition of N has declined slightly at SDEF since 1986 (NADP 2019a), possibly reflecting more stringent regulation of automobile emissions adopted in California. However, NADP protocols used at SDEF do not effectively capture dry deposition of N compounds. Recent throughfall measurements at SDEF were used to estimate average deposition

rates of 23 kg N/ha/yr (Fenn, n.d.), indicating that total N deposition has not declined, despite reduced emissions, and suggesting that the SDEF is a N-saturated system.

Measured levels of NO_3^- in SDEF stream water did not decline from the late 1980s through 2001 (Meixner et al. 2006). The suspension of water quality monitoring at SDEF since 2002, extended by the recent drought, prevented more current collection of stream water NO_3^- until 2017, and these recent results have yet to be analyzed. As a result, it is not possible to tell whether SDEF stream NO_3^- levels have mirrored trends in total atmospheric deposition of N over the past decade. At some other experimental forests and ranges (EFRs), stream water NO_3^- has followed trends in atmospheric deposition of N (see chapter 3, Hubbard Brook Experimental Forest, and chapter 14, Coweeta Hydrologic Laboratory), but not all EFRs have reflected this pattern (see chapter 2, Marcell Experimental Forest, and chapter 13, Fernow Experimental Forest).

Stream water P has not been monitored regularly at SDEF, but levels in downstream rivers are fairly low (~ 0.5 mg phosphate [PO_4^{3-}]-P/L) (Council for Watershed Health 2012). A comparable nearby site, with relatively undisturbed chaparral vegetation, had stream water total P ranging from 0.02 to 0.07 mg/L (Stein and Yoon 2007), suggesting that total P at SDEF is probably also low.

Biological responses of aquatic species or groups to N and P—

No work has been done at SDEF on the biological responses of aquatic species or functional groups to stream water nutrients. However, stream nutrient observations at SDEF provide indications of whole stream biological activity. Dissolved N concentrations and fluxes are the net result of biologically mediated processes throughout the watershed that sequester, mobilize, or transform the various forms of N. For example, Riggan et al. (1985) reported that experimental NO_3^- additions to stream water at SDEF were greatly attenuated, presumably by biological uptake, when sampled 150 and 300 m downstream. Furthermore, the measured low concentrations in summer base flow indicated high levels of biological uptake of NO_3^- in summer, while larger fluxes of NO_3^- during major winter storms implied reduced biological uptake in winter (Riggan et al. 1985).

A study of several major streams in neighboring Los Angeles and Ventura Counties found that in shaded reaches, diatom cover was positively associated with total P and negatively associated with total N, while in unshaded reaches, algal cover was positively associated with total N and negatively associated with total P. Also, while the cover of algae was generally not detrimental to benthic macroinvertebrates, the cover of diatoms was negatively associated with specific indicators of a healthy invertebrate community (Ambrose et al. 2003). Data from 104 southern California streams, spanning broad nutrient gradients, revealed that the relative abundance of N_2 -fixing heterocystous cyanobacteria decreased with

increasing ambient inorganic N concentrations within the low end of the N gradient (Stancheva et al. 2013). Similar patterns may prevail at SDEF, but no studies have been performed to test this assumption.

Effects of streamflow on nutrients—

Flux of NO_3^- in stream water is positively correlated with stream discharge, and annual NO_3^- yield is greater in wet years than dry years. Concentrations of NO_3^- are greatest during late summer and early autumn, presumably because storms wash accumulated N deposition off vegetation. However, NO_3^- flux is substantial only during major winter storms that saturate the soil mantle, producing overland flow and throughflow that directly enter streams (Riggan et al. 1985).

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

Other factors studied at SDEF that can influence the biological responses in streams include streamflow, water temperature, and suspended sediment. Streamflow monitoring on SDEF started at 14 watersheds in 1938. With infrastructure deterioration and funding limitations, only five gaging stations remain in operation. Records are discontinuous, with monitoring interrupted following the wildfires of 1960 and 2002. Flow usually commences in the late fall after several large storm events totaling ~150 mm or more and often continues until late spring. During dry years, including the drought of 2012–2016, no flow was recorded. In wet years, streams flowed the entire year. Digital thermometers were added to stream gaging stations in 1999. Suspended sediment was measured for 5 years following the wildfire in 1960 in conjunction with small watershed sediment yield studies.

Reference Watersheds

Two reference watersheds have been continuously managed for minimal human disturbance under native chaparral vegetation and have been monitored for water quality: Volfe Canyon, a drainage of 300 ha, and Bell 3, a drainage of 25 ha. Streamflow has been measured at the outlet of both catchments since the late 1930s, and stream water NO_3^- was monitored from the mid-1980s to 2002. Both watersheds were burned by wildland fires in 1960 and again in 2002. General vegetation surveys of this area were made in the 1930s, and a soil survey was conducted in the early 1960s. Surveys of aquatic organisms have not been performed. Although the large influx of atmospheric deposition and air pollution from the Los Angeles Basin and recurring wildland fires may preclude describing them as strictly pristine, these reference watersheds still likely represent minimally managed headwater basins in the region because air pollution and wildland fire are widespread in southern California.

Cross-Site and Regional Studies

Unlike most other regions where headwater streams are usually less polluted than downstream waters, the levels of NO_3^- in stream water in SDEF headwaters are much higher than concentrations downstream in the San Gabriel River measured by regional watershed-wide monitoring (Council for Watershed Health 2012). This suggests that as N is transported in these streams, it is being altered by some combination of biological uptake leading to sequestration, dilution by lesser impaired waters, and denitrification. Denitrification may be favored in hotspots with anaerobic conditions and an available carbon source such as sediment deposits or vegetated riparian edges.

Atmospheric deposition data collected at SDEF have been used in the development of regional and national assessments and maps of wet deposition rates of N pollutants done periodically by NADP (NADP 2019b). Moreover, patterns of atmospheric deposition have been well documented in southern California along gradients from areas of high- to relatively low-pollution, largely driven by proximity to urban centers and topography (Fenn and Kiefer 1999, Fenn et al. 2010, Padgett et al. 2014). Source water NO_3^- levels generally increased along these gradients of pollution loading across southern California (Riggan et al. 1985).

Monitored streams within the San Gabriel River drainage basin, at elevations both higher and lower than SDEF, exhibited lower NO_3^- levels than SDEF (California Water Resources Control Board 2017). This suggests that perhaps SDEF may lie within an elevation band that receives enhanced N deposition, coinciding with the top of the regional inversion layer at ~1000 m altitude.

Data from SDEF has also been used in a national comparison of stream water NO_3^- measured at sites across the EFR network. The stream water NO_3^- concentrations from the reference watersheds at SDEF are one to two orders of magnitude greater than forested reference watersheds in other regions of the country, all of which also have lower levels of N deposition than SDEF (Argerich et al. 2013). Research results from several EFR sites, with which SDEF was compared, are presented in other chapters in this volume.

Responses to Management and Natural Disturbances

Some of the watersheds in SDEF were deliberately type converted from native chaparral to nonnative grass vegetation following a wildland fire in 1960. The purpose of this paired watershed experiment was to determine if replacing the deep-rooted chaparral shrubs with shallow-rooted grasses would increase water yield for downstream human use. Water yields were, and continue to be, significantly higher in the treated watersheds compared to the untreated reference

basins. Twenty years posttreatment, greater concentrations and yields of NO_3^- were measured in watersheds that had been type converted to grasslands (Meixner and Wohlgemuth 2003). Presumably, the greater NO_3^- levels reflected greater subsurface soil exposure caused by landslides in these altered landscapes (Rice et al. 1969), coupled with the more rapid water flux through the shallow-rooted grasses. Maximum measured yield was 19.4 kg N/ha/yr in grass vegetation compared to 10.0 kg N/ha/yr in chaparral (Riggan et al. 1985). Elevated NO_3^- levels along with quicker hydrologic response continue to characterize the type-converted watersheds to the present (USDA FS, n.d.).

Wildland fire is the main driver of natural disturbance in the mountains of southern California. Wildland fires can greatly accelerate NO_3^- loading by mineralizing the N accumulated in the vegetation and leaf litter and producing ash that surface runoff transports to streams. Coupled with increased stream discharge associated with burned watersheds (Hamilton et al. 1954, Krammes and Rice 1963), this NO_3^- flush to aquatic systems may affect downstream waters and aquifers. Following a prescribed fire, initial flows produced stream water NO_3^- -N concentrations as high as 15.7 mg/L or 1.5 times the federal drinking water standard (Riggan et al. 1985). Export of NO_3^- increased with fire severity, and levels remained elevated for as long as 5 to 10 years postfire compared to nearby unburned watersheds (Meixner et al. 2003, 2006; Riggan et al. 1994). Export of P also increased after wildfires from P adsorbed on ash and sediment that were transported by streams in initial postfire runoff (Meixner and Wohlgemuth 2004).

Postfire flooding, accelerated erosion, debris flows, and downstream sedimentation have all been documented on SDEF (Dunn et al. 1988, Wohlgemuth 2008, Wohlgemuth and Hubbert 2008). The massive flux of both water and sediment from burned hillsides can create major changes in fluvial geomorphology and aquatic habitats. Although stream biological communities and processes are probably altered in postfire environments by increased nutrient fluxes and drastic physical disturbances (Minshall 2003), biological responses after fires have not been studied at SDEF.

Reliability and Limitations of Findings

The results of the monitoring and research on SDEF should be applicable to the chaparral lands of southern California that are similarly affected by high levels of N deposition. Outside this zone of high pollution and away from urban centers, SDEF data should be applied with caution. In cases of uncertainty, where air pollution or other site characteristics deviate from SDEF, validation monitoring or studies might be beneficial to test how well SDEF findings represent the local conditions.

Research Needs

From the perspective of the water quality regulatory community, the highest priority science question that could be answered at SDEF is, Has total N deposition at SDEF declined or remained stable since the early 1980s, considering the declining trend of wet deposition of N; and, concurrently, has SDEF stream water NO_3^- followed the declining trend in wet N atmospheric deposition since 2002? Answering this question would be important to regulators because it might provide a scientific basis for anticipating how NO_3^- levels in headwater streams, a source of NO_3^- pollution in southern California, might respond to future changes in air pollution levels and associated atmospheric deposition of N. To address this question, future research at SDEF would need to include (1) systematically measuring current total atmospheric deposition of N to the vegetation canopy at SDEF using methods that could be validly compared with the previous measurements, (2) performing a thorough analysis of existing SDEF stream water monitoring NO_3^- data to investigate whether changes in stream water nitrate levels have reflected trends in deposition of N since the mid-1980s, and (3) resuming monitoring of SDEF stream water NO_3^- .

Potential Utility to Water Quality Regulatory Agencies

Water quality regulatory agencies might use SDEF for a number of practical purposes. For example, they might use existing SDEF research findings and datasets for developing total maximum daily loads or to model effects of wildland fire or effects of air pollution and N deposition on NO_3^- levels in headwater streams during other planning efforts. Regulators might also use SDEF reference watersheds to provide a baseline of nutrient conditions that are typical of otherwise undisturbed mountain headwater basins in southern California that receive high air pollution loads. In this region, even undisturbed headwaters areas have received high levels of atmospheric deposition of N and have burned regularly in wildland fires. Unlike SDEF, background conditions in many urbanized Los Angeles Basin stream systems have been confounded by the anthropogenic effects of fertilizer runoff or hydromodification that have strongly influenced nutrients and biological conditions.

Key points:

- Measured NO_3^- concentrations and yields in SDEF reference streams are one to two orders of magnitude greater than low N deposition sites in southern California.
- Source of the NO_3^- at SDEF is primarily air pollution from the Los Angeles Basin that is deposited to the chaparral canopy and subsequently washed off by rain.

- Nitrate flux in stream water was positively correlated with stream discharge, and annual watershed NO_3^- yields were greater in higher rainfall years.
- Wildfires greatly accelerated the NO_3^- loading to streams, and elevated levels of NO_3^- persisted for years after a burn.
- Catchments that were type converted from native chaparral to grasslands had greater NO_3^- concentrations and yields in stream water.
- SDEF stream water nutrient data provide estimates of general biological uptake by stream ecosystems, but no work has been done at SDEF on biological responses to nutrients of aquatic species or functional groups.
- The science gap at SDEF of highest priority for the regulatory community is to understand whether atmospheric deposition of total N has changed since the early 1980s and whether NO_3^- in SDEF stream water have mirrored any change in total deposition of N over that period.
- Regulatory agencies might use existing SDEF data and research findings to model effects of N deposition or wildland fire on headwater stream NO_3^- in southern California.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Currently, there are no pressing regional issues of concern related to nutrients other than N and P.

Findings From Studies

Weekly measurements of the amounts of calcium, magnesium, potassium, sodium, hydrogen ion, chloride, and sulfate are routinely performed in wet deposition samples at SDEF following established protocols of the NADP network. However, none of these nutrients have been monitored in SDEF stream water, and no work has been done on biological responses to them in streams at SDEF.

Studies of Other Factors

As noted in the section on stream N and P, other factors that can influence biological responses in streams have been monitored at SDEF including streamflow, water temperature, and suspended sediment. These factors would probably also affect biological responses to nutrients other than N and P.

Cross-Site and Regional Studies

Although SDEF has not participated in the regional water quality monitoring in the San Gabriel River drainage, this network has measured dissolved organic and inorganic carbon as well as silica in numerous streams in the area around SDEF (Council for Watershed Health 2012). Atmospheric deposition of nutrients other than N, collected at SDEF have been used in the development of periodic regional and national assessments and maps of deposition by NADP (NADP 2019b).

Reference Watersheds

Streams on reference watersheds at SDEF have not been monitored for nutrients other than N.

Response to Management and Natural Disturbances

It is not known whether there were any effects from nutrients other than N in SDEF streams from management activities such as type conversion, prescribed burning, or wildfire because these nutrients have not been studied.

Research Needs

Research and monitoring of nutrients other than N or P are not a high priority for regulatory agencies in this region, so no priority science gaps on this topic were identified.

Potential Utility to Water Quality Regulatory Agencies

Presently, water quality regulatory agencies have little need for research and monitoring results on nutrients other than N or P. However, if any new concerns were to arise about impacts of these other nutrients on the beneficial uses of water, long-term atmospheric deposition data of these nutrients, collected at the NADP site in SDEF, would be available for use by regulators in the region. However, only wet deposition data are measured by NADP monitoring, which is less than half of total atmospheric deposition in this dry-deposition-dominated ecosystem (Fenn et al. 2012).

Key points:

- There are no pressing regional concerns about nutrients other than N and P, and, except for long-term wet deposition monitoring, little work has been done at SDEF on these nutrients.
- Monitoring of some nutrients other than N or P has been conducted by regional agencies in the downstream San Gabriel River basin, but SDEF has not participated in this network.

Overview and Synthesis

Streams at SDEF have been the site of long-term monitoring of streamflow, stream NO_3^- , and, intermittently, suspended sediment and water temperature. Stream water from SDEF has had very high levels of NO_3^- owing to air pollution-derived atmospheric deposition of N. Reference watersheds at SDEF may be useful to the regulatory community as examples of streams with minimal human disturbance, but subject to combined effects from high levels of air pollution and periodic wild-land fires. Unlike many streams in the region, SDEF streams have not been affected by urban runoff or hydromodification. Levels of NO_3^- in headwater stream water at SDEF are much higher than at downstream waters, representing a gradient that is not usual outside of this region.

Wildfires at SDEF have increased stream NO_3^- loading, sedimentation, and turbidity for years after a burn. Watershed vegetation type conversion from chaparral to grass can further increase stream nitrate concentrations and yields. However, apart from whole stream uptake of NO_3^- , no work at SDEF has directly examined biological responses to nutrients.

The highest priority science question for the regulatory community at SDEF is, Has total atmospheric deposition of N at SDEF changed since the 1980s, and has nitrate in SDEF stream water tracked changes in total N deposition? Answering this question might be important for regulatory agencies because it might provide them with a scientific basis for anticipating how NO_3^- levels in headwater streams in this region might respond to future changes in air pollution and N deposition. These streams are sources of NO_3^- to aquifers that are used for drinking water supplies, so better understanding of what controls their water quality might be useful in developing regulations that protect human health. Filling this knowledge gap at SDEF would require remeasuring total atmospheric deposition of N, using methods comparable to the previous measurement in the 1980s, analyzing trends in SDEF stream water NO_3^- data since the early 1980s, and reestablishing the monitoring of NO_3^- in SDEF streams.

If the regulatory community wanted to use SDEF to investigate biological responses to nutrients or other environmental factors, they might consider establishing aquatic bioassessment sites on the SDEF streams. Routine monitoring at SDEF might provide environmental context for interpreting bioassessment results, and further insights might be gained, for example, if monitoring of chlorophyll *a* were added at SDEF. In addition, regulatory agencies might benefit if data from SDEF were incorporated into local and statewide databases such as the California Environmental Data Exchange Network (California Water Resources Control Board 2017). Any future research or monitoring undertaken at SDEF to address the

needs of the regulatory community would benefit from collaboration among water quality regulatory agencies, the USFS, and university investigators and coordination with ongoing state and regional water quality monitoring programs.

Key points:

- SDEF is the site of detailed and long-term monitoring and studies of stream physical factors and stream water NO_3^- , but almost no studies of stream biology.
- Reference watersheds at SDEF represent baseline conditions in headwaters in the region with minimal onsite human disturbance but high atmospheric deposition of N and periodic wildland fires.
- Effects of N deposition on headwater stream NO_3^- , a critical information need of regional regulatory agencies, might be addressed by future work at SDEF.
- Regulatory agencies could establish bioassessment sites on SDEF streams to take advantage of routine monitoring and research already done on those streams.
- Research or monitoring at SDEF, to meet the needs of regulators, would best be undertaken through collaboration between state, federal, and other interested investigators.

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Chapter 17: Ecoregion Not Classified: Luquillo Experimental Forest, Puerto Rico

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Introduction

This chapter is a review and synthesis of research conducted at Luquillo Experimental Forest (LEF) 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 (EPA) and the Puerto Rico Department of Natural and Environmental Resources, about existing results of relevant scientific studies that are available at LEF, and to identify future field and synthetic research of potential use to regulatory agencies that might be conducted at LEF.

Site Description

LEF encompasses 11 500 ha within El Yunque National Forest in northeastern Puerto Rico (lat. 18.3° N, long. 65.8° W). Steep, mountainous terrain dominates LEF, with deep valleys separated by high, knife-like ridges. Elevations in LEF range from valley bottoms at ~200 m to El Toro Peak at 1065 m. Rainfall is high with a strong elevation gradient ranging from 2500 mm/yr at lower elevations to ≥4500 mm/yr at upper elevations. Air temperature ranges from 15 to 30 °C year-round (McDowell et al. 2012).

LEF is predominantly forested, with four tropical rainforest types present at different elevations or topographic positions. Tabonuco forest dominates at 300 to 550 m elevation, while colorado forest dominates from 550 to 800 m, and elfin forest dominates above 800 m. Sierra palm forests are found in valley bottoms and ridge tops at any elevation (Murphy et al. 2012). Land use has been closely monitored and tightly controlled for research purposes within LEF. In recent decades, many areas bordering LEF have experienced urban or suburban development, while other areas have been allowed to regenerate forest cover following cessation of agriculture (Gould et al. 2012).

Four main watersheds drain LEF: the Rio Mameyes in the north, the Rio Fajardo in the east, the Rio Icacos/Blanco in the south, and the Rio Espiritu Santo

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in the west (fig. 17.1). Because of the abundant year-round rainfall, a dense network of perennial headwater streams drain this landscape of steep mountain flanks. Hurricanes have strongly influenced the hydrology, biota, and nutrient cycling of streams at LEF. Streams in LEF are extremely flashy and have steep, often rocky or boulder-strewn channels (Murphy and Stallard 2012).

Bedrock is mostly Cretaceous, volcanoclastic, sedimentary, and marine-deposited, with intrusions of the Eocene Rio Blanco quartz diorite. Contact metamorphism surrounding intrusions produced harder hornfels-type rock that underlay the highest peaks (Murphy et al. 2012). Watersheds with quartz diorite bedrock have lower channel slopes and sandy, meandering channels. Upland soils on the quartz diorite consist of loam Inceptisols with high quartz content, while soils on the volcanoclastic bedrock largely consist of clay and clay loam Inceptisols and Oxisols, with little quartz. Soil water flowpaths through the volcanoclastic-derived soils tend to be shallow owing to high abundance of occluding clays (McDowell et al. 2012).

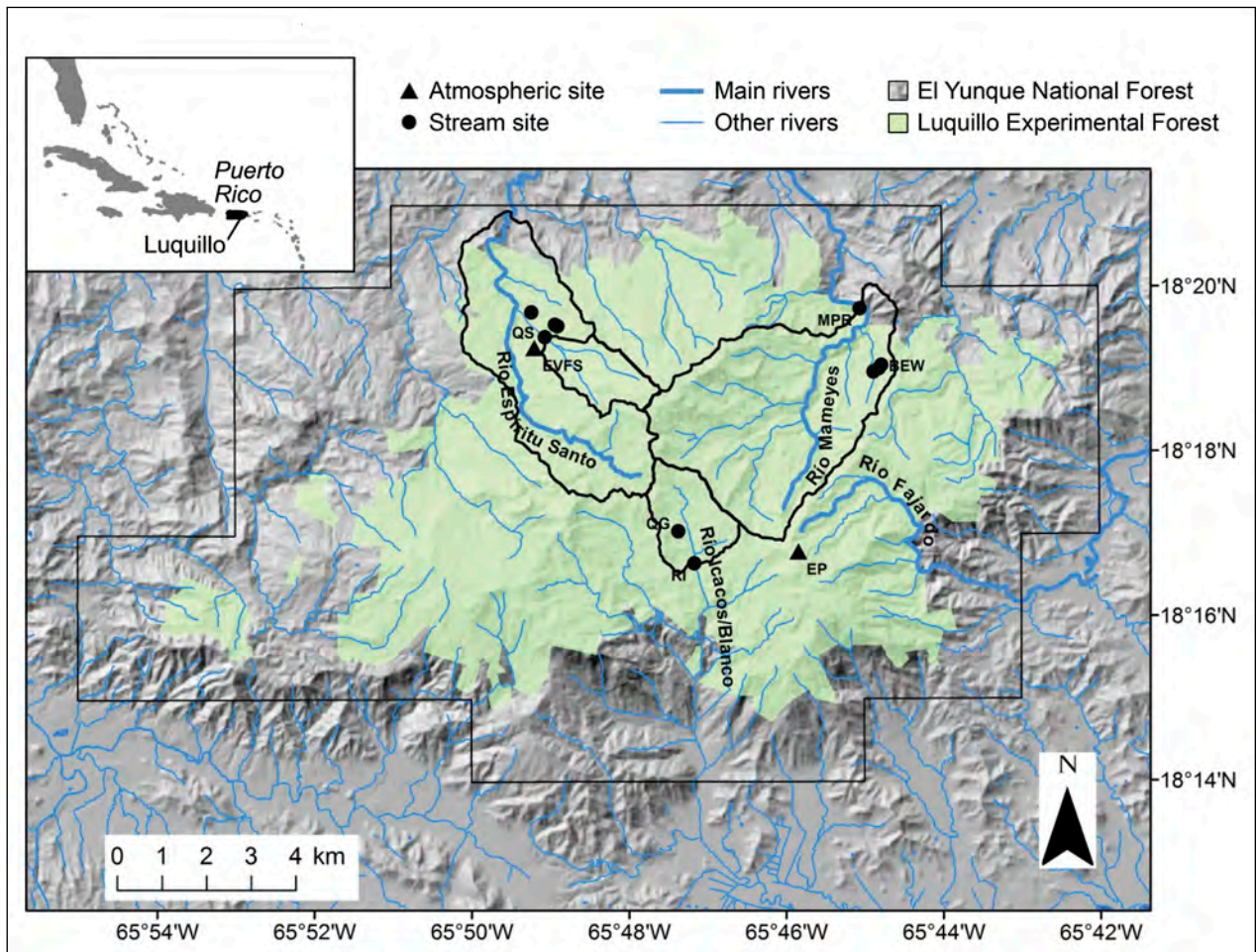


Figure 17.1—The Luquillo Experimental Forest, including locations of major reference watersheds (BEW = Bisley Experimental Watersheds; MPR = Rio Mameyes-Puente Roto; RI = Rio Icacos; QG = Quebrada Guaba; QS = Quebrada Sonadora) and atmospheric input monitoring sites (EP = East Peak; EVFS = El Verde Field Station).

Research History

The U.S. Forest Service (USFS) established LEF in 1956 to broaden the scope of research in tropical forestry, although natural history and forestry studies had been conducted at this site since the early 20th century. Previously, the Tropical Forest Experiment Station had been established in 1939 to provide a scientific basis for reforestation following several destructive hurricanes in the 1920s and 1930s, and was later renamed the International Institute of Tropical Forestry (IITF) (Wadsworth 1995). Work at LEF on sustainable forest production, including pine and mahogany plantations, produced important contributions to the literature on tropical forestry worldwide (Lugo et al. 2006, Lugo and Heartsill Scalley 2014, Wadsworth 1995).

IITF expanded from its original focus on forestry to conduct a broad range of continuing ecological and watershed studies in LEF. Studies of ecological structure and function, including water quality, hydrology, and watershed management, emerged from earlier forestry research (Brown et al. 1983, Lugo et al. 2006). Continuous stream gaging began in 1968, although sporadic flow monitoring had been conducted since the 1940s. Stream hydrology and chemistry studies began in the 1960s (Cuevas and Clements 1975). Modern ecological research in LEF also started in the 1960s, with 5 years of monitoring and experimentation on ecosystem processes as part of the Rain Forest Project supported by the U.S. Atomic Energy Commission (Odum 1970).

The U.S. Geological Survey (USGS) has a long record of hydrology and stream chemistry research at LEF. Water quality monitoring at USGS stations began in the 1960s and has continued to the present. As part of the Water, Energy and Biogeochemical Budgets (WEBB) program, USGS has published stream monitoring data from three LEF reference watersheds (Rio Mameyes, Rio Icacos, and Quebrada Guaba), along with two nearby watersheds with agricultural land use, in a 15-year study of watershed solute and sediment flux (USDI GS 2014).

In 1988, LEF became a member site of the Long Term Ecological Research (LTER) Network, sponsored by the National Science Foundation (NSF). As an LTER participant, LEF established regular stream nutrient monitoring as part of a program of multiscale, integrated ecosystem studies. In addition, LEF has been a member site in the NSF's Critical Zone Observatory (CZO) network since 2009, which has included studies of stream solutes, sediments, and nutrients.

Availability of publications and data—

For more details about the work at Luquillo LTER, including a detailed site description and a comprehensive list of publications, see LTER Network (2017a). Many datasets collected by LEF studies are on the LTER Network's online repository (LTER Network 2017b). Long-term daily streamflow and weather data from LEF that are formatted for ready comparison with other experimental forests and ranges,

(EFRs) and LTER sites may be downloaded at the ClimDB/HydroDB website (LTER Network 2013). USFS publications on LEF and related journal articles can be downloaded from the IITF website (USDA FS 2017). The Luquillo CZO website (CZO 2017) also has an online data repository and a list of publications.

Biological Responses to Stream Nutrients N and P

Issues of Concern

Tropical and Neotropical forests have undergone the highest rates of deforestation and land use change of any forest type since the mid-20th century (Lindquist et al. 2012). Land use change in Puerto Rico over this period, outside of LEF, has largely run counter to trends elsewhere in the tropics, with substantial reforestation occurring on Puerto Rico's abandoned agricultural areas (Gould et al. 2012). Urban and suburban land development has also proceeded since the mid-20th century. Abandoned agricultural lands have either been urbanized or have naturally afforested with a mix of native and exotic species that together constitute a novel ecosystem (Lugo and Helmer 2004, Morse et al. 2014). LEF study basins are drained by rare and valuable examples of reference streams in tropical forests, against which streams draining urbanized and regenerating forest watersheds in Puerto Rico and elsewhere in the tropics can be compared (Heartsill Scalley and Lopez-Marrero 2014).

Urban development of watersheds downstream of LEF has caused increased nitrogen (N) and phosphorus (P) loading, as well as changes to other factors that may affect stream biota, including light availability, temperature, dissolved oxygen (DO), dissolved organic carbon (DOC), suspended sediment, channel structure, and streamflow (de Jesús-Crespo and Ramírez 2011, Potter et al. 2014, Ramírez et al. 2014, Santos-Román et al. 2003). Urban wastewater discharge from publicly owned treatment works and suburban/rural septic systems are major vectors of N and P enrichment to streams (Figueroa-Nieves et al. 2014). Excessive N and P loading can degrade water quality for beneficial uses such as drinking water, recreation, and aquatic ecosystem integrity.

Drinking water quality is of great concern for Puerto Rico's headwater streams, because streams that drain forested uplands are major sources of the island's clean drinking water. For example, more than 20 percent of Puerto Rico's population relies on drinking water primarily from streams leaving LEF (Scatena and Johnson 2001). Diversion of flow from streams leaving LEF has intensified recently, increasing from 54 percent in the 1990s to 70 percent in 2004 (Crook et al. 2007).

In addition to threatening local drinking water, excessive N and P loads can degrade water quality in sensitive downstream estuaries and coastal ecosystems, such as mangrove forests, seagrass beds, and coral reefs, which are important nurseries for many fish stocks and attractions for the tourism industry.

Atmospheric deposition of nutrients in precipitation, dust, and aerosols is a concern in many regions. Puerto Rico receives atmospherically deposited nutrients via long-range transport from distant sources such as dust originating from the Sahara Desert (McDowell et al. 1990, Pett-Ridge 2009).

Effects of global climate change on streams are also of concern in Puerto Rico. Hurricane-driven forest disturbance caused changes in N loading in LEF watersheds, and climate models predict intense hurricanes to become more frequent in the North Atlantic as climate warms (Emanuel 2013, Knutson et al. 2010).

Climate change may also cause impacts on LEF streams from drought, a concern that was recently highlighted by low rainfall in 2015. Despite wetter conditions in recent years in Hispaniola (Comarazamy et al. 2015), and in Puerto Rico from 2001 to 2013 (Van Beusekom et al. 2015), coupled climate-water cycle models predict a high likelihood that drought will become more frequent and severe in the Caribbean region owing to climate change (Prudhomme et al. 2014). Drought has complex impacts on stream biota, including indirect impacts via changing nutrient status. In dry periods, streams can experience low flows that concentrate nutrients as flow volume decreases, even if nutrient inputs remain constant. Reduced flows can also directly alter habitat for aquatic organisms by shrinking channel area and decreasing water available for transpiration by riparian plants.

Findings From Studies

Overall N and P conditions in streams—

Nitrate (NO_3^-)-N, ammonium (NH_4^+)-N, total dissolved nitrogen, and phosphate (PO_4^{3-})-P have been monitored weekly in LEF watersheds: Sonadora, Toronja, and Icacos since 1983, Bisley 1–3 since 1988, and Mameyes-Puente Roto and Prieta since 1989 (McDowell and Asbury 1994, Schaefer et al. 2000).

Concentrations and fluxes of N in LEF streams were higher than in most temperate forested reference watersheds, as is common in tropical and subtropical forests (Brookshire et al. 2012, Hedin et al. 2009, Lewis et al. 1999). Concentrations of NO_3^- were particularly high ($\geq 100 \mu\text{g NO}_3^- \text{-N/L}$) compared to other forested reference streams. NO_3^- concentration was unrelated to discharge, indicating biotic control (McDowell and Asbury 1994, Shanley et al. 2011). Flux of NO_3^- was controlled by total runoff, which, in turn, is a function of the elevation gradient of precipitation (McDowell and Asbury 1994). Dissolved P concentrations and export were low to moderate, a feature common in other tropical forest streams. Iron and aluminum oxides in soils bind PO_4^{3-} strongly in soils, immobilizing P and delaying transport to streams via leaching (Liptzin and Silver 2009).

LEF is upwind of sources of air pollution local to Puerto Rico, which makes it an ideal site to monitor regional-to-global-scale atmospheric N inputs. The National Atmospheric Deposition Program (NADP) has been monitoring wet deposition of N

at LEF since 1985 (NADP 2019). Stallard (2001) and Ortiz-Zayas et al. (2006) both reported a significant increase in wet N deposition from 1985 to 2003, but since then, N deposition has not increased (Stallard 2012). At current rates of 2 to 3.5 kg N/ha/yr, wet deposition of N is not considered a major vector of stream enrichment in Puerto Rico but might become an issue if atmospheric deposition of N increased in the future.

Data on dry deposition of N and P from windborne dust or aerosols are lacking for LEF and Puerto Rico in general, although throughfall, which is precipitation collected beneath the plant canopy, has been extensively studied. Throughfall washes the products of dry deposition off the canopy, and at LEF is significantly enriched in NO_3^- -N, NH_4^+ -N, and P compared to rain water collected in open areas (Heartsill Scalley et al. 2007, McDowell 1998, McDowell et al. 1990).

Enrichment with P is not considered a concern in headwater streams, such as those within LEF. Deposition of dust carried from the Sahara Desert across the Atlantic Ocean by the trade winds has been estimated to be a significant input of P to LEF watersheds, totaling 0.23 kg P/ha/yr, or slightly larger than the average input from bedrock weathering (Pett-Ridge 2009). Deposition from this transoceanic source is strongly seasonal, peaking in June and July (Stallard 2012). Although it is unclear how future P delivery from Saharan dust may be affected by climate change, at current levels, this source is not a major vector of P enrichment to streams.

Ability of streams to regulate N and P dynamics—

Organisms in LEF streams actively cycle N between the water column and benthic food webs. Uptake of the inorganic forms NH_4^+ and NO_3^- has been studied in detail. An enrichment study using isotopically tagged $^{15}\text{NH}_4^+$ showed that NH_4^+ uptake was dominated by nitrification rather than assimilation (Merriam et al. 2002). Trace amounts of $^{15}\text{NH}_4^+$ were continuously added over a 42-day period to a stream in an LEF watershed, Bisley 3. Detailed accounting of the fate of added ^{15}N showed rapid stream NH_4^+ uptake, of which 60 percent was due to nitrification. Over the study period, 65 percent of the isotopic tracer was exported in all forms, but only 1 percent was exported as $^{15}\text{NH}_4^+$, indicating that the stream actively processed 99 percent of the added $^{15}\text{NH}_4^+$. Fifty percent of added ^{15}N was exported as NO_3^- , 8 percent as DON, and 6 percent as particulate N. Of the 45 percent of added ^{15}N that was retained, most was in fine benthic organic matter and epilithon, which amounted to 10 and 6 percent, respectively, of the total amount added. Less than 1 percent of added ^{15}N was retained in leaves, wood, insects, shrimp, and crabs combined.

Potter et al. (2010) conducted isotopically tagged $^{15}\text{NO}_3^-$ additions lasting 24 hours in three LEF streams to quantify NO_3^- uptake and denitrification. Uptake was dominated by autotrophic rather than heterotrophic assimilation. Denitrification was a significant pathway, averaging a third of total uptake.

Although P dynamics have been less studied in LEF streams than N dynamics, Benstead et al. (2010) reported significant uptake of PO_4^{3-} in Bisley 3 and Prieta streams.

Consumers in higher trophic levels exert indirect influences on N and P dynamics in LEF streams. The most important consumers in LEF stream food webs are decapods consisting of three genera of freshwater shrimp (*Atya* spp., *Xiphocaris elongata*, and *Macrobrachium* spp.) and one genera of freshwater crab (*Epilobocera sinuatifrons*) (Covich and McDowell 1996; Pérez-Reyes et al. 2015, 2016; Zimmerman and Covich 2003). There are numerous reports of streams dominated by shrimp and crabs in tropical landscapes (Boulton et al. 2008, Jacobsen et al. 2008, Rincón and Covich 2014, chapter 18 on Hawai'i Experimental Tropical Forest). In early phases of their life cycles, shrimp species in LEF streams migrate to salt water and return upstream to mature and reproduce. Wright and Covich (2005) found that LEF shrimp fill important ecological niches that are often occupied by insect taxa in temperate streams, such as shredders, scrapers, filterers, and predators. In LEF streams, *Atya* spp. and *X. elongata* exerted top-down control over the benthic resource base, with indirect impact on N and P (Benstead et al. 2010, Crowl et al. 2001, Pringle et al. 1999). Grazing by *Atya* and detrital processing by *X. elongata* limited accumulation of N and P in autotrophic biomass and fine particulate organic matter standing stock. This grazing released nutrients for uptake and assimilation by autotrophs, and increased leaf litter decay rates. Greathouse et al. (2006) observed that reaches of streams above dams that excluded shrimp had far greater benthic organic matter and N standing stocks than did streams with shrimp.

Fish and snails are also important consumers in LEF streams, except in streams above cascades or steep waterfalls that are barriers to their upstream passage (Covich et al. 2009, Crowl et al. 2012, McDowell et al. 2012). Mountain mullet (*Agonostomus monticola*) are present up to ~400 m elevation and prey on shrimp, possibly releasing grazing pressure on autotrophs. Goby (*Sicydium plumieri*) are important algivores that can be found up to ~700 m elevation because they are capable of climbing dispersal barriers using suction-cup-shaped pectoral appendages. Herbivorous neritid snails (*Neritina* spp.) can climb the steepest inclines but generally are not found upstream of waterfalls, possibly because of short lifespans and the energetic demands of migration (Pyron and Covich 2003). Surveys have found the highest densities of shrimp upstream of the ranges of fish and snails (Covich et al. 2009, Greathouse and Pringle 2006, Hein et al. 2011).

Effects of N and P on LEF stream food webs and ecosystem processes—

To test N and P limitation on biofilm growth, Tank and Dodds (2003) deployed artificial substrates that diffused N and P, both separately and in combination, into LEF streams and monitored chlorophyll *a* production by epilithic and epixylic

biofilms. Bisley showed low chlorophyll *a* production in all treatments and no additional biofilm growth with added N or P; the P enrichment showed less growth than the control. No other LEF streams have been tested for N and P limitation of biofilms. No studies of the response of submerged or riparian vegetation to nutrients have been conducted at LEF.

Studies have also found no effects on decomposition and dissolved organic matter uptake in response to increased N and P availability in LEF streams. Tank and Dodds (2003) studied fungal biomass production on wooden disks with N or P enrichment. They found that ergosterol, a fungal biomarker, did not increase with N or P enrichment, providing evidence that wood-decomposing fungi are not limited by these nutrients. In a Costa Rican tropical forest stream, however, Rosemond et al. (2002) studied rates of leaf litter breakdown in a number of streams that constituted a natural P concentration gradient. They found that leaves broke down faster in the higher P streams, suggesting P-limitation of heterotrophic activity. No similar study has yet been conducted at LEF.

High NO_3^- concentrations in LEF streams have been attributed to high nitrification rates in soils and streams (Merriam et al. 2002). The watersheds on quartz diorite bedrock had high NH_4^+ concentrations in groundwater flowing through riparian zones, potentially supplying the stream with ample substrate for nitrification. In contrast, volcanoclastic watersheds had nearly undetectable levels of NH_4^+ in riparian groundwater. Riparian zones removed up to 90 percent of N from groundwater before it reached streams (Chestnut and McDowell 2000, McDowell et al. 1992). Where NH_4^+ was available to stream biota, nitrifying microorganisms using NH_4^+ as an energy source were able to compete with microorganisms using NH_4^+ as a nutrient (Merriam et al. 2002).

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

Periods of drought in LEF have complex impacts on stream biota and food webs, causing accelerated rates of leaf senescence in terrestrial vegetation and litter delivery to streams, which, combined with a lack of flushing, leads to accumulation in streams of litter and organic debris. During the 1994 drought, pool depth decreased and aquatic habitat contracted, causing crowding and disrupting reproductive capacity among shrimp (Covich et al. 2003). Although these impacts on biota might be expected to alter stream N and P dynamics, no changes in LEF stream N and P concentrations were reported during the droughts of 1989, 1991, or 1994. Preliminary results from the drought of 2015 also suggest no change in N and P concentrations (McDowell, n.d.).

Frequent high flows in LEF streams might also be expected to affect biotic response to N and P. For example, scouring might limit periphyton biomass and

thereby limit periphyton nutrient uptake, but Ortiz-Zayas et al. (2005) reported no decrease in periphyton biomass after high flows in an LEF stream. Relationships between discharge and concentration have been used in recent years to improve predictions of solute flux at high flows as well as to make inferences about watershed sources and sinks of solutes and suspended materials. The lack of response of NO_3^- concentration to discharge in LEF watersheds is thought to indicate that NO_3^- is under biotic control, likely a result of both terrestrial and aquatic immobilization (McDowell and Asbury 1994, Shanley et al. 2011).

Tank and Dodds (2003) observed that light availability at the stream surface was low ($0.3 \text{ mol/m}^2/\text{d}$) beneath LEF's dense canopy. Consistent with low available light, undisturbed streams were highly heterotrophic. Even low-elevation reaches were predominantly heterotrophic, despite wider channel widths that permitted more light to reach the benthic surface (Ortiz-Zayas et al. 2005). In wider reaches, strong grazing pressure by shrimp may have limited autotrophic standing crop, rather than available light.

Food webs in LEF streams depend heavily on litter inputs from riparian vegetation as a source of energy (Covich and McDowell 1996). High nitrification rates in Bisley have led to the hypothesis that NH_4^+ is also an important additional energy source to overall benthic metabolism and that energy demand regulates NH_4^+ uptake in these tropical forested streams (Merriam et al. 2002).

Water temperatures in LEF streams range from 17 to 30 °C. Stream temperatures generally decrease with altitude and show much less seasonal and diurnal variation than temperate forest streams (Brown et al. 1983, McDowell and Asbury 1994, Ortiz-Zayas et al. 2005, Stallard and Murphy 2012).

Reference Watersheds and Monitoring Sites

All LEF study watersheds have been formally designated as reference watersheds. They have been managed for minimal onsite human disturbance since LEF was established in 1956, and before that land use consisted of scattered, low-intensity agriculture, forestry, and mining. These LEF study basins are increasingly rare and valuable examples of well-studied reference conditions against which streams elsewhere in Puerto Rico and in the wet tropics worldwide can be compared. All of the research findings from LEF streams reported in this chapter are based on work done in these LEF reference streams.

Reference watersheds at LEF were selected on northeastern, northern, and southern flanks of the Luquillo Mountains to encompass the range of environmental conditions, particularly rainfall, which vary with aspect in response to the prevailing northeast trade winds.

The Rio Mameyes study watershed drains 1782 ha on the steep northeastern slope of the Luquillo Mountains, at 83 to 1050 m elevation. Mameyes was 99

percent forested when it was acquired by USFS in the 1930s, although parts of the basin had previously experienced selective logging and small-scale agriculture at lower elevations (Murphy et al. 2012). Agriculture was largely abandoned following a destructive 1899 hurricane (Scatena 1989). USGS has continuously measured discharge and rainfall at the watershed outlet since 1967.

The Bisley experimental watersheds, within the Rio Mameyes basin, have been managed as reference watersheds since their acquisition by the USFS in 1934. Bisley 1 watershed has an area of 7 ha, Bisley 2 an area of 6 ha, and Bisley 3 an area of 35 ha. Three gaged streams, two meteorological stations, soil and vegetation plots, and groundwater monitoring wells are located within the Bisley watersheds. Groundwater chemistry and hydrology in the riparian zone of Bisley 3 have been monitored intermittently since 1985 to the present. Rainfall and throughfall chemistry were monitored regularly at Bisley from 1988 to 2007.

Three reference watersheds are located at the El Verde research area within the Rio Espiritu Santo basin on the northern flank of the Luquillo Mountains. They consist of Quebrada Sonadora, with an area of 262 ha; Quebrada Toronja, with an area of 51 ha; and Quebrada Prieta, with an area of 31 ha. Wet deposition chemistry has been monitored at the El Verde Field Station since 1985 (NADP 2019).

Rio Icacos is a 326-ha reference watershed located high on the southern flank of the Luquillo Mountains at 620 to 832 m elevation. It is dominated by colorado forest with abundant sierra palm forest on ridges and in riparian zones. The Icacos basin had very little logging and no agriculture before acquisition by the USFS. USGS has continuously monitored stream discharge since 1968 and precipitation since 1989. Stream chemistry has been monitored weekly since the 1980s, and frequent event-based sampling was conducted by the USGS WEBB project in the 1990s and early 2000s. Groundwater chemistry and hydrology in the riparian zone of a small tributary to the Rio Icacos have been monitored intermittently from 1985 through 2010 and quarterly from 2011 to the present. Quebrada Guaba, another subwatershed of Rio Icacos, has had water chemistry monitored with weekly, continuous and event-based sampling. Meteorological data, wet deposition chemistry, and airborne dust chemistry are also monitored continuously at East Peak (1030 m), which flanks the Rio Icacos watershed.

Argerich et al. (2013) reported that over the period 1987–2007, Bisley 2, Bisley 3, and Sonadora all showed significant decreasing trends in monthly flow-weighted stream water NO_3^- concentrations. From 1997 through 2007, stream NO_3^- in these three watersheds, plus Bisley 1, also significantly decreased. They offered no explanations for these trends.

Cross-Site and Regional Studies

Streams in LEF have been included in numerous cross-site, regional, and global studies of stream nutrient flux because LEF has one of the most detailed stream

chemistry records of any tropical or subtropical forest. LEF data were used to develop N and P criteria for water quality regulations across Puerto Rico. Sotomayor et al. (2011) made recommendations for N and P criteria using archived USGS water chemistry data from 57 stations across Puerto Rico that included six forested reference sites across Puerto Rico, three of which are LEF reference watersheds (Icacos, Mameyes-Puente Roto, and Sonadora).

Comparisons of developed vs. undeveloped watersheds in Puerto Rico have used LEF data. Santos-Roman et al. (2003) used water quality monitoring data from 15 sites across Puerto Rico, including two within LEF, and demonstrated that N and P concentrations were lower and overall water quality conditions were better in forested watersheds than urban watersheds. Stallard and Murphy (2012) compared stream chemistry findings from the USGS WEBB project for Icacos, and Mameyes, with two watersheds with historical or current agricultural influences. Concentrations and yields of NO_3^- , NH_4^+ , and PO_4^{3-} were higher in the developed watersheds, which the authors attributed to agricultural activities and domestic waste disposal.

Biological communities in urban streams with high N and P, draining watersheds outside of LEF, have been compared to LEF streams. In the Rio Piedras watershed, in the San Juan metropolitan area, macroinvertebrate communities shifted from sensitive taxa, such as mayflies (Ephemeroptera) and caddisflies (Trichoptera), to tolerant taxa such as midges (Diptera: Chironomidae), with increasing urban density (de Jesús-Crespo and Ramírez 2011, Ramírez et al. 2009). These studies did not measure shrimp or crab populations, but did report sightings in the urban watersheds. Greathouse et al. (2006) reported that grazing by atyid shrimp kept rock surfaces clean even in streams with high N levels of 1.5 mg NO_3^- -N/L. Native diadromous fish species, such as *A. monticola* that migrate between salt- and freshwater, also persisted in urban streams without physical barriers to fish passage (Ramírez et al. 2009). The presence of decapods and fish in urban streams outside LEF indicate that enrichment with N and P do not necessarily exclude them, although lack of population measurements prevented quantitative comparisons with reference streams.

Lewis et al. (1999) included data from Icacos, Sonadora, and Toronja in a multiregional analysis of stream N exports from 31 relatively undisturbed watersheds, consisting of 25 tropical streams from mostly American tropical forests and savannas, and six forested streams in California. Fluxes of all forms of N were found to be correlated with total runoff. Icacos ranked high in NO_3^- export among the studied watersheds owing to its high runoff.

Argerich et al. (2013) analyzed trends over time in NO_3^- and NH_4^+ concentrations in forested reference streams at seven EFRs across the United States, including four LEF catchments. The reference streams at some other EFRs, including Hubbard Brook Experimental Forest in New Hampshire (see chapter 3) and H.J. Andrews Experimental Forest in Oregon (see chapter 5) showed

decreasing trends in NO_3^- -N concentration as did the LEF streams. However, these EFRs have very different environments, and the authors did not speculate whether causes of these trends have anything in common among these otherwise dissimilar sites.

LEF has also been the site of two cross-site experimental studies of stream N cycling, the first and second Lotic Intersite Nitrogen eXperiments (LINX I and LINX II). In LINX I, stable isotope enrichment experiments using $^{15}\text{NH}_4^+$ were conducted at 10 North American stream sites from Arctic tundra to tropical forest (see Peterson et al. 2001 for overview). The LEF was the only tropical stream in the study (Merriam et al. 2002). Nitrification in the LEF stream (Bisley 1) accounted for the largest fraction of total NH_4^+ uptake of any of the streams studied in LINX I, although the absolute rate of nitrification was higher in a North Carolina stream (Webster et al. 2003). Forest streams at LEF plus North Carolina and Oregon experienced no N or N + P limitation on biofilm growth. All three of these sites had very low average light availability (Tank and Dodds 2003), suggesting that light may commonly limit biofilm production in streams under heavy canopy cover.

Potter et al. (2010) reported the effects of $^{15}\text{NO}_3^-$ enrichments on streams at eight sites across North America that were part of LINX II. At each of the eight sites, streams were selected to represent reference, agricultural, and urban land use (Mulholland et al. 2008). In Puerto Rico, three LEF streams were used as reference sites and compared with three agricultural and three urban streams. As expected, ambient NO_3^- -N and NH_4^+ -N concentrations were lowest in the LEF streams and highest in the urban streams. Across all land uses, the Puerto Rican streams showed NO_3^- uptake that was strongly correlated with background NO_3^- -N concentration, indicating that stream organisms/communities had some capacity to adapt to higher NO_3^- loads than under reference conditions by processing more NO_3^- . In addition, NO_3^- uptake was strongly correlated with gross primary productivity, suggesting that light exerts an indirect control on uptake where autotrophs are active. Denitrification in all Puerto Rican streams accounted for a third of total NO_3^- uptake on average, and denitrification rates were positively correlated with DOC concentrations.

Responses to Management and Natural Disturbance

Most LEF research on effects of forest management has focused not on streams but on forest biomass production. In the 1930s and 1940s, over 2300 ha of mahogany, teak, and pine plantations were planted at lower elevations of LEF, and timber production was monitored. Experimental studies examined the effects of cutting and

herbicides on regrowth of vegetation. The Rain Forest Project (Odum and Pigeon 1970) examined effects of an experimental irradiation with radioactive cesium, which, at highest exposures, was lethal to vegetation on a 50-ha forest plot. Potential impacts of management practices on groundwater or streams have not been studied, nor have LEF research findings been used to develop any best management practices (BMPs) for water quality protection.

Hurricanes and landslides are the major natural causes of disturbances. As noted above, hurricane-related disturbance caused large increases in stream NO_3^- -N concentrations that took years to decades to return to predisturbance baseline (McDowell et al. 2013, Schaefer et al. 2000, Shanley et al. 2011). No posthurricane increases in P have been observed. Following Hurricane Hugo in 1989, Shanley et al. (2011) showed that NO_3^- -N exports from Icacos in the 1990s were roughly double those of the prehurricane 1980s. Groundwater N in hurricane-disturbed riparian zones showed a similar pattern to stream water NO_3^- , increasing for years to decades following disturbance (McDowell et al. 1996, 2013).

Hurricane disturbance of forests has long been recognized as a major driver of N dynamics in tropical forest streams, owing in part to research in LEF. Hurricanes affect stream N dynamics indirectly by wind-damaging trees, causing tree mortality, and by greatly increasing delivery of fresh leaf and wood litter to the forest floor and stream channel. Following Hurricane Hugo in 1989, loss of vegetative uptake and increased litter decomposition caused posthurricane increases in NO_3^- -N concentrations and N export that took years to decades to return to prehurricane levels (Schaefer et al. 2000). A similar pattern was repeated following Hurricane Georges in 1998 (McDowell et al. 2013). Maximum posthurricane stream NO_3^- concentrations were 0.37 mg NO_3^- -N/L, several times higher than prehurricane concentrations, but below the federal drinking water standard of 10 mg NO_3^- -N/L. P dynamics showed no response to hurricane disturbance, either because mineralized P did not reach the stream or because mineralization of biomass-bound P was insufficient to raise stream water concentrations above background.

The Luquillo LTER Canopy Trimming Experiment (CTE) simulated the biophysical disturbances that accompany hurricanes (LTER Network 2015). Its purpose was to distinguish nutrient fluxes in soil solution caused by canopy opening vs. fluxes caused by wood and leaf debris. Neither canopy opening nor debris addition, on their own, produced elevated NO_3^- -N flux in soil, but in combination they produced peaks in NO_3^- -N concentrations lasting 18 months, which were similar to the posthurricane response of NO_3^- in streams (McDowell and Liptzin 2014). Levels in soil solution increased from 0.01 to 0.03 mg NO_3^- -N/L to nearly 7.5 mg NO_3^- -N/L over the first 10 months of the full hurricane simulation.

Both reduced vegetative N demand, and increased mineralization of organically bound N in litter appear to be necessary to produce a NO_3^- pulse in soil solution that was similar to the observed posthurricane pulse in stream water. Evidence from the CTE has strengthened the argument that regrowth of trees causes the hurricane-induced pulse of increased stream N concentrations to eventually decline to prehurricane levels. Dissolved PO_4^{3-} in soil solution did not respond to canopy trimming treatments.

Although direct effects on stream biota of a hurricane-induced N pulse have not been studied, posthurricane biological responses to increased channel inputs of plant litter have been reported. Shrimp populations temporarily increased in response to the abundance of litter inputs and debris dams from Hurricane Hugo, and then declined as prehurricane conditions returned over the following year (Covich et al. 1991). These temporary population booms may have altered nutrient cycling, considering that shrimp exert control on the benthic resource base, but any effects on N and P were not studied.

Reliability and Limitations of Findings

Research results and environmental monitoring datasets from LEF apply most directly to streams at other sites in Puerto Rico with relatively undisturbed forests, particularly where climate and geology are most similar to LEF's. At sites where these factors are dissimilar to LEF's, or where high accuracy is required, validation experiments or monitoring should be considered to test how well findings from LEF predict local conditions.

LEF streams have extremely flashy hydrology that makes study of stormflow conditions difficult and hazardous. As a result, most research has been conducted at base flow conditions, which may not detect the important processes that take place during stormflows. USGS used autosamplers during the WEBB project to obtain grab samples at higher runoff rates than any other studies previously published (Stallard and Murphy 2012), and sensors have recently been deployed at LEF to continuously record DO and conductivity. However, field experiments remain difficult and often dangerous during high flows, and the scarcity of stream data collected during high flow events has limited parameterization of models of nutrient effects on LEF stream biota at high flows.

Research Needs

The highest priority research question for the water quality regulatory community related to N and P that could be filled at LEF is, How does flow reduction owing to drought or water withdrawal affect stream biotic responses to N and P?

Filling this need would be important for the regulatory community because regulators require information on the capacity of stream biota to cope with the interactive effects of flow reduction and nutrient enrichment, especially considering predictions of increased drought frequency and severity. Compared to the impacts of hurricanes, relatively little is known about how drought conditions affect biological responses to N and P in rainforest streams. In periods of low flow, stream biotic processing of nutrients might mitigate the loss of dilution capacity by streams, or, alternatively, stream biota might be negatively affected by low flows and lose their natural capacity to process nutrients. If the latter is the case, stream nutrient levels would rise, perhaps making more costly wastewater treatment necessary in order to meet standards for protected uses. LEF shrimp survey data have been used to determine instream flow, the minimum required flow for preserving a given set of ecological functions (Scatena and Johnson 2001), but no study has considered the effect of low flow on nutrients. As discussed above, low flows during the drought of 1994 caused both crowding of shrimp and accumulations of leaf litter, suggesting a limit on the ability of shrimp to break down leaf litter, but the mechanism of this limit are not known (Covich et al. 2003). A better understanding of stream biotic response to drought might offer the potential to improve modeling for nutrient total maximum daily load (TMDL) models. If this research need were filled, water quality regulators might be better informed to decide when it might be necessary to modify nutrient endorsements during periods of low flows.

The following work would need to be done at LEF to fill this research need: (1) reanalyze existing LEF long-term rainfall, streamflow, and stream nutrient datasets to develop a quantitative model of drought effects on stream nutrient concentrations; (2) initiate focused monitoring of nutrient conditions and biotic surveys at low flows; (3) conduct nutrient uptake experiments during low flows; and (4) study biological responses to experimental flow reductions and drying of natural or artificially created streams.

Other relevant questions that might be addressed at LEF, but are of lower priority for regulators include the following:

- Can responses to global drivers such as climate change and atmospheric deposition of N and P be detected by monitoring LEF's forested, low-nutrient streams under reference conditions?
- How do N and P levels affect stream metabolism and biological oxygen demand export downstream?
- In LEF forested catchments, streams export a higher proportion of the total N load as dissolved organic nitrogen, while urbanized catchments

typically export a larger fraction as dissolved inorganic nitrogen. Do these differences reflect differences in N sources or differences in aquatic N cycling?

- Are the organic forms of N and P in LEF watersheds more or less labile than the organic N and P in urban watersheds or in wastewater?
- Is the marine environment a significant source of nutrients to tropical coastal streams via migrating shrimp and fishes? What fraction of stream N and P is delivered to streams from marine environments, how much is taken up in freshwater food webs, and how much returns to the ocean as stream flux?
- Do large floods alter stream nutrient conditions on an enduring basis?

Potential Utility to Water Quality Regulatory Agencies

Responses of ecosystems at LEF to disturbances, such as hurricanes and droughts, can be interpreted without the confounding effects of a complex land use history. In this context, watersheds at LEF might be useful to water quality regulatory agencies both as natural reference points for comparison with Puerto Rico's urban-impacted watersheds, and as sentinels of regional-to-global-scale drivers such as climate change and N deposition.

Long-term data on N and P concentrations and fluxes in LEF streams might be used to improve estimates of "best attainable" concentrations for the establishment of nutrient criteria for Puerto Rico streams. Nutrient criteria to protect biological and chemical integrity of inland waters in Puerto Rico are not in place but are in development (Sotomayor et al. 2011). LEF stream chemistry datasets might augment the datasets currently being used for this purpose. Similarly, LEF stream data might also be used to represent background "natural" nonpoint source loads for determining nutrient TMDLs for streams elsewhere in Puerto Rico.

Stream biological parameters, such as typical assemblages of aquatic organisms, and decapod and fish survey data, have been extensively studied at LEF. These data might be used to assist the development of indicators of stream biological integrity because detailed representations of unaffected biotic conditions are rare for Puerto Rican streams with low nutrient inputs.

Lastly, LEF research findings on the capacity of headwater streams and riparian zones to retain N might be used to establish BMPs for riparian buffer conservation. LEF findings demonstrate how important intact forested riparian zones and headwater streams are for protecting water quality and the biological integrity of streams in Puerto Rico and possibly elsewhere in the tropics.

Key points:

- LEF streams have characteristics typical of undisturbed tropical forests under natural conditions, such as relatively high N and low P concentrations.
- LEF stream biota have the ability to control N and P dynamics via microbial uptake of inorganic N and food web interactions, such as detrital processing and grazing on algae by shrimp that prevent accumulation of autotrophic biomass.
- Although food web effects on N and P have been extensively studied, many important questions remain unanswered about how N and P levels affect food webs.
- Low light conditions and scant DOC inputs to LEF streams limit energy available to biota and cause microbial nitrification of NH_4^+ to be an important energy source.
- From the perspective of the regulatory community, the highest priority research question that could be filled at LEF is, How does flow reduction owing to drought or water withdrawal affect stream biotic responses to N and P?
- Existing LEF datasets and research results might be used by regulators to establish nutrients criteria, to identify stream health bioindicators, and to develop BMPs for conserving riparian buffers for Puerto Rico.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Nutrients other than N and P do not currently present issues of concern in Puerto Rico's streams, but their export and delivery to rivers, estuaries, and coastal waters may affect the functioning of those downstream ecosystems. For example, concentration and flux of silicone dioxide (SiO_2) are high in LEF watersheds relative to temperate forested streams, owing to rapid weathering of primary minerals in bedrock. In downstream estuaries and offshore marine environments, SiO_2 limitation of primary productivity by diatoms is common because diatoms require SiO_2 to grow their siliceous frustules, or shells. Changes in SiO_2 flux from uplands might alter diatom production at the base of food webs in estuaries and coastal ecosystems.

In Puerto Rico, urbanization and atmospheric deposition also add nutrients other than N and P to streams. Urbanization can increase chloride (Cl^-) two- to threefold above concentrations in reference streams. Atmospheric deposition of sulfate (SO_4^{2-}) is of concern because, in excess, it may acidify streams, although

moderate-level SO_4^{2-} loading might alleviate sulfur limitation of terrestrial vegetation or aquatic microorganisms.

While not a nutrient for the purposes of this synthesis, DOC merits discussion because it is tightly coupled with nutrient cycling in aquatic ecosystems and can be an energy source for the base of aquatic food webs. DOC loads are low in LEF streams but are much higher in urban streams in Puerto Rico. Wastewater discharge can cause DOC enrichment and change the molecular composition of the DOC pool in streams (Figueroa-Nieves et al. 2014, Potter et al. 2014). Elevated DOC loads, especially more labile forms in wastewater, supports high stream bacterial populations and contribute to oxygen depletion.

Findings From Studies

Overall conditions of nutrients other than N and P—

Stream water calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), Cl^- , bromide (Br^-), SO_4^{2-} , and SiO_2 have been monitored on a weekly basis in LEF reference watersheds Sonadora, Toronja, and Icacos since 1983; Bisley 1–3 since 1988; and Mameyes-Puente Roto and Prieta since 1989 (McDowell and Asbury 1994, Schaefer et al. 2000). The dynamics of Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , Br^- , and SiO_2 are largely controlled by flow conditions, with strong dilution as flows increase. Additional controls also have been inferred from effects of hurricane-related disturbance on K^+ , from spatial variability of dissolved SiO_2 , and from the concentration-discharge relationships for SO_4^{2-} . Weekly monitoring for these constituents in wet deposition has occurred since 1985 at the El Verde site (NADP 2019). Wet deposition of SO_4^{2-} has increased in LEF precipitation, as has total acidity, since NADP monitoring began. Stallard (2012) attributed this increase to pollutants from temperate zone sources.

Bedrock weathering and sea salt aerosol inputs supply base cations to LEF streams (McDowell et al. 1990, McDowell and Asbury 1994). High SiO_2 concentrations (≥ 25 mg SiO_2/L) are a ubiquitous feature of LEF streams owing to high rates of bedrock weathering from year-round abundant moisture and warm temperatures.

Responses of stream biota to nutrients other than N and P have not been studied extensively in LEF streams. It is likely that none of these other nutrients are biologically limiting, because their stream water concentrations, driven by inputs from weathering and sea salt aerosols, are thought to be sufficient to support stream biological processes (Stallard and Murphy 2012).

Ability of streams to regulate dynamics of nutrients other than N and P—

Silica cycling by freshwater diatoms have not been studied at LEF. The role of terrestrial vegetation in the watershed SiO_2 cycle has been examined in the Icacos watershed. Studies have assessed sources of SiO_2 to the stream using a novel

geochemical technique, the ratio of germanium to silicon (Ge/Si) in stream water, soil solution, and minerals in soil and bedrock (Derry et al. 2005, Lugolobi et al. 2010). Previously, Derry et al. (2005) had applied this technique to Hawai'ian watersheds and shown that most of the SiO_2 in riverine flux had been cycled by terrestrial vegetation. At LEF, however, Lugolobi et al. (2010) found that terrestrial plants actively cycle only a small fraction of SiO_2 close to the soil surface, retaining it from streamflow.

The SO_4^{2-} concentration-discharge relationship is markedly different from Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , and SiO_2 . Instead of strong dilution at higher flows, SO_4^{2-} concentrations show little response to changing discharge (McDowell and Asbury 1994, Shanley et al. 2011). This difference in the behavior of SO_4^{2-} from these other constituents suggests that biotic factors influence SO_4^{2-} , but the exact mechanism is unknown. Sulfur cycling within streams has not been studied in detail.

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

Numerous other factors that might influence biotic responses have been measured at LEF. These are the same factors that were mentioned earlier in the chapter as possibly influencing responses to N and P: flow conditions, light, and organic matter. Low light levels, for example, probably exert strong influence on SiO_2 cycling, as light limitation of diatom growth can suppress SiO_2 demand in streams.

Streams in LEF have low DOC concentrations during base flows. McDowell (1998) attributed this condition to high sorption capacity in the clayey soils limiting supply to streams, and to high stream respiration rates that indicate DOC may be rapidly mineralized (Ortiz-Zayas et al. 2005). A strong positive concentration-discharge relationship holds, with DOC increasing from 2 to 20 mg DOC-C/L from low to high flows, except at highest flows when the relationship changes to a negative slope (McDowell and Asbury 1994, Shanley et al. 2011). LEF streams and groundwater are often supersaturated with carbon dioxide (CO_2), indicating that high soil respiration and high weathering rates supply CO_2 that eventually is exported as bicarbonate or degasses from the stream surface. Riparian zones retained large amounts of DOC from groundwater before it reached streams. Chestnut and McDowell (2000) estimated that without riparian processing, one headwater stream in the Icacos basin would have a fourfold higher DOC concentration. Some important aspects of stream carbon budgets have not yet been quantified at LEF, including the fraction of CO_2 produced by stream respiration, the amount of CO_2 lost from streams by evasion, and the contribution of autochthonous production to the stream DOC pool.

Cross-Site and Regional Studies

Monitoring data collected at LEF for nutrients other than N and P are used in regional and national analyses and maps of atmospheric deposition regularly produced by the NADP Network (NADP 2019). Stallard (2012) synthesized these data to analyze concentrations, loads, and trends in precipitation for the WEBB watersheds in northeastern Puerto Rico.

Stallard and Murphy (2012) reported stream chemistry findings from the USGS WEBB project for Icacos, Mameyes, and two other watersheds with both historical and current agricultural influences. Concentrations of Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , SO_4^{2-} , and SiO_2 were higher in the developed watersheds, which the authors attributed to agricultural activities and domestic waste disposal.

Studies of urban watersheds near LEF have elucidated the effects of urbanization on stream water Na^+ , Cl^- , and DOC. Santos-Román et al. (2003) showed that among 15 watersheds across Puerto Rico, urban basins had higher Na^+ and Cl^- concentrations than forested watersheds, including two in LEF. Potter et al. (2014) found that Cl^- and DOC concentrations in subbasins of the urban Rio Piedras watershed were positively correlated with spatial density of sewer pipes, suggesting that both constituents reach surface waters via leaks or illicit discharges. Chloride concentrations averaged 34 mg Cl^-/L with a maximum of 52 mg Cl^-/L . These concentrations were below EPA recommendations for aquatic life criteria of 200 mg Cl^-/L , but more than three times the highest concentrations in LEF reference watersheds. Concentrations of DOC were similarly enriched, with a maximum of 11 mg $\text{DOC-C}/\text{L}$.

Effluent from wastewater treatment in Puerto Rico significantly changes the DOC composition of streams, including some downstream of LEF (Figueroa-Nieves et al. 2014). Effluent shifts urban streams toward more labile DOC, which is more readily taken up by bacteria and respired, consuming DO in the process.

In a study of chemical weathering deduced from solute fluxes in stream water, White et al. (1998) found that Rio Icacos had the highest known weathering rates in the world for a granitic watershed, likely owing to high precipitation and a young pluton particularly susceptible to weathering (Stallard and Murphy 2012).

Responses to Management and Natural Disturbances

Concentrations and fluxes of nutrients other than N and P have been shown to be insensitive to hurricane disturbance in LEF, with the exception of K^+ . In simulated hurricane treatments of the CTE, McDowell and Liptzin (2014) did not observe any response of DOC in soil solution.

The K^+ cycle is an important biogeochemical marker of tropical forest disturbance and recovery. Stream concentrations and export of K^+ were increased after

hurricane disturbance of whole watersheds on a similar time scale to N (McDowell et al. 2013, Schaefer et al. 2000). This K^+ pulse was the result of mineralization of tree litter added to the soil by hurricane damage, as tree biomass was the largest K^+ pool in LEF systems (McDowell 1998). Schaefer et al. (2000) found that Hurricane Hugo had approximately doubled K^+ flux from LEF watersheds during the first year posthurricane. Although K^+ pulses in streams are probably a typical feature of whole-watershed responses to hurricane disturbances in the tropics, McDowell and Liptzin (2014) reported no K^+ pulse in soil solution in the CTE study, despite observing a NO_3^- pulse. They attributed the lack of an expected K^+ response to a lag in data collection that probably missed a rapid K^+ pulse in the first months after the simulated hurricane treatment.

Landslides occur frequently in LEF watersheds and often intersect the dense drainage network. Landslides directly affect LEF streams by delivering sediment to stream channels (Larsen 2012). Bhatt and McDowell (2007) attributed the higher concentrations of SiO_2 observed in springs at higher elevations to the exposure and weathering of fresh bedrock by landslides. Even in heavily forested LEF watersheds, the presence of roads increases the likelihood of landslides. Larsen (2012) found that 43 to 63 percent of landslide-related erosion in Icacos and Mameyes was associated with roads.

Reliability and Limitations of Findings

Scientific findings and monitoring datasets from LEF related to nutrients other than N and P probably apply to other watersheds in Puerto Rico with climate and land use similar to LEF. Where environmental factors differ from LEF, or where a high degree of accuracy is required, we suggest considering validation experiments or monitoring in order to test how well LEF results predict local conditions.

Research Needs

The highest priority research question for the water quality regulatory community related to nutrients other than N and P that could be answered at LEF is, Do tropical forested headwater streams actively process DOC, and does that processing affect aquatic food webs both in headwaters and downstream in second- and third-order streams?

Answering this question would be important for the regulatory community because DOC will either be used as an energy resource for stream food webs, as a source of mineralized nutrients, or be passively transported downstream to estuaries and coastal waters. The fate of DOC depends on its composition and on the environmental conditions and microbial communities it encounters in transit. If DOC is mineralized in streams, it will contribute to DO depletion and release

organically bound nutrients. If DOC is not mineralized in headwater streams, background levels of DOC loading will probably be driven by riparian and instream DOC sources and by streamflow. Knowledge of DOC loading and active processing in headwater streams, such as those at LEF, might help water quality regulators better understand what background DOC would be in undisturbed streams for assessing effects of urban DOC enrichment from wastewater discharges.

The following work would need to be done at LEF to answer this question: (1) conduct assays of biodegradable DOC with incubations to determine DOC losses under different flow conditions; (2) conduct field or mesocosm enrichment experiments using different compositions of DOC, such as leaf litter leachate, glucose or acetate, and wastewater DOC; and (3) develop a quantitative model of DOC mineralization that incorporates effects of source and molecular composition.

Other relevant questions that might be addressed at LEF, but of lower priority for regulators include the following:

- Do tropical forested headwater streams exert any control on the SiO_2 cycle and downstream export from forested reference watersheds, or do they passively transport SiO_2 to downstream ecosystems?
- Do tropical forested headwater streams actively cycle SO_4^{2-} , or do they passively transport SO_4^{2-} to downstream ecosystems?

Potential Utility to Water Quality Regulatory Agencies

As noted above related to N and P, the LEF provides an invaluable background of conditions for nutrients other than N and P against which urbanized or other heavily managed streams may be compared, and also as a baseline for assessing responses to regional or global-scale drivers of change. Parallel to riparian processing of groundwater N, LEF-based findings that riparian zones retain groundwater DOC might provide a scientific basis for BMPs to mitigate DOC delivery to streams by conserving intact riparian zones. LEF also has extensive, long-term monitoring datasets on nutrients other than N and P that might be used by regulators should issues arise in the future concerning these other nutrients.

Key points:

- Potassium concentrations and fluxes increase greatly after hurricane-driven forest disturbance compared to prehurricane conditions.
- Silica can be a limiting nutrient in marine systems, and silica concentrations and exports are high in LEF streams owing to the high weathering rates of the underlying rocks.

- LEF streams carry low DOC loads, but nearby urban streams carry elevated DOC concentrations of labile forms from wastewater that may enhance DO depletion.
- The fate of DOC in headwater streams is a high-priority research need of water quality regulators that might be addressed by future LEF research.
- Continuous monitoring datasets of nutrients other than N and P from LEF watersheds from the 1980s to present are readily available for use by water quality regulators.

Overview and Synthesis

The LEF may be thought of as an island within an island, where largely intact, mountain forests are surrounded by a heavily urbanized landscape, all situated on an oceanic, tropical island. Free from the impacts of development, the green island of LEF has served for decades as an environmental laboratory for the study of important ecological functions, including processes that control the quality of water from these forest-dominated watersheds. Below, along densely populated coasts, the urban island of Puerto Rico is critically dependent on the green interior uplands to provide clean freshwater. These headwater streams also provide habitat that supports healthy communities of native aquatic species.

Research from LEF provides the most complete water quality baseline that exists for Puerto Rico and for tropical forest streams without confounding impacts from land uses. Past and future studies conducted at LEF may prove essential to disentangling the effects of global and regional drivers of change, such as drought and hurricanes, from the effects of local drivers such as urban development.

Many LEF studies discussed here have examined how streams process nutrients, showing that terrestrial inputs control fluxes of nutrients and organic matter in forest streams; that shrimp are the dominant organisms processing plant detritus in streams; and that natural disturbances, including hurricanes and landslides, strongly influence long-term stream nutrient dynamics. Fewer studies have addressed how stream biota respond to nutrients. Future work at LEF can broaden the scope of research to include more aspects of the responses of the biological community to stream nutrients. A better understanding of how LEF stream biota are affected by nutrients will undoubtedly be of use as regulatory agencies develop criteria to protect ecological function and maintain ecosystem services, such as providing clean water for the people of Puerto Rico.

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Chapter 18: Ecoregion Not Classified: Hawai'i Experimental Tropical Forest, Hawai'i

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Introduction

This chapter is a review and synthesis of research conducted at Hawai'i Experimental Tropical Forest (HETF) 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 and the Hawai'i Department of Land and Natural Resources (DLNR), about existing results of relevant scientific studies that are available at HETF, and to identify future field and synthetic research of potential use to regulatory agencies that might be conducted at HETF.

Site Description

HETF was established in 2007 by the U.S. Forest Service (USFS), and Hawai'i DLNR, Division of Forestry and Wildlife, and Division of State Parks. The HETF is composed of two units, both located on the Island of Hawai'i: the Laupāhoehoe Wet Forest (LWF) (4990 ha) and the Pu'u Wa'awa'a Dry Forest (PWDF) (15 736 ha). HETF is located on DLNR-managed lands with the following designations: forest reserve and natural area reserve in LWF and forest bird sanctuary, forest reserve, and state parks in PWDF.

The LWF (lat. 19° 56' 13.74" N, long. 155° 16' 37.08" W) is located on the eastern flank of Mauna Kea Volcano from 500 to 2000 m elevation (fig. 18.1). The vegetation is a tropical montane forest dominated by native 'ōhi'a (*Metrosideros polymorpha* Gaudich.) and koa (*Acacia koa* A. Gray) trees, although at its lower boundary, LWF has been heavily invaded by the exotic strawberry guava tree (*Psidium cattleianum*, Afzel. ex Sabine). Mean annual rainfall ranges from 2900 to 4060 mm/yr across steeply sloped forested headwater basins that are underlain by 4,000- to 250,000-year-old weathered tephra. Predominant soils are composed of moderately to well-drained hydrous, ferrihydritic/amorphous, isothermic/isomesic Acrudoxic Hydruclands of the 'Akaka, Honoka'a, Maile, and Pi'ihonua soil series

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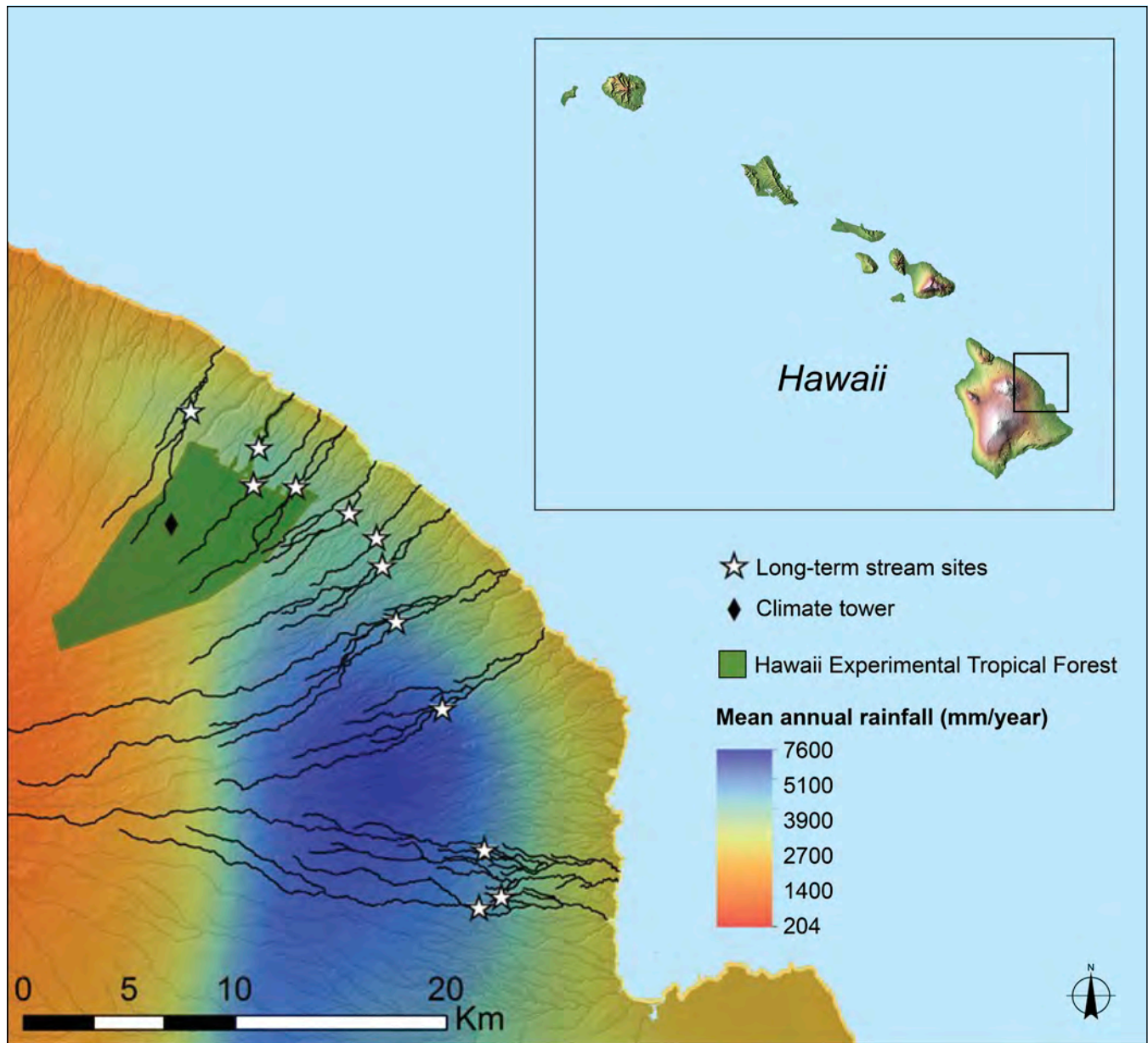


Figure 18.1—Permanent research stream sites in the Climate Change and Pacific Island Water Resources study along the North Hilo Coast of Hawai'i Island, including those located in the Laupāhoehoe Wet Forest of the Hawai'i Experimental Tropical Forest. Stream study sites shown are (N-S) Ka'awali'i, Manowai'ōpae, Kaiwilahilahi, Pāhale, Makahiloa, Manoloa, Waikaumalo, 'Uma'uma, Kolekole, Kapu'e, Pā'hoehoe, and Honoli'i.

(Litton et al. 2011). Seven major streams drain the LWF: Ha'akoa, Ka'awali'i, Kaiwilahilahi, Kilau, Laupāhoehoe, Manowai'ōpae, and Pāhale (fig. 18.1). Streams consist of a series of channel units composed of runs, riffles, and pools separated by waterfalls, cascades, or chutes. Stream slopes are typically greater than 10 percent, resulting in streambed materials that vary from gravel and cobble to bedrock and boulder, and generally lack sand and silt. Flows rapidly respond to extreme rainfall events, with base flows shifting to flashflood conditions in minutes (Larned and San-

tos 2000, Lau and Mink 2006, Oki 2003, Tomlinson and DeCarlo 2003). As defined by Hansen (2001), streams within LWF are naturally intermittent. They have flow during most of the year owing to short-term bank storage inputs that maintain stream base flow. Runoff from precipitation is a supplemental source of water for streamflow in these streams. During extreme dry periods, these streams may not have flowing water. At lower elevation, these streams flow year-round. A few streams within LWF have structures installed for withdrawing water, but they are in disrepair and no longer remove water. The LWF is the location of stream monitoring in HETF.

The PWDF tract of HTEF (lat. 19° 47' 29.33" N, long. 155° 50' 52.79" W) is located on the North Kona coast on the leeward, dry side of the Island of Hawai'i. PWDF is not a focus of this chapter because its low rainfall and permeable bedrock produce no surface streams.

Stream biological communities—

Hawai'i's remoteness from continental landmasses, combined with mountainous terrain, has produced highly endemic assemblages of stream organisms. Surveys of stream fauna outside of HETF have reported that Hawai'ian streams are dominated by endemic gobies, snails, and shrimp that exhibit an amphidromous life cycle in which adults live and spawn upstream (Kinzie 1993, McDowall 1997). Freshwater floods allow shrimp larvae to drift quickly downstream to the ocean. These larvae are morphologically and physiologically adapted to live in salt water, with only days to get to the ocean, although this may differ with individual taxa (Hogan et al. 2014; Miller, n.d.). Once larvae reach the ocean, they reside in the water column and continue to eat and grow until they develop into postlarvae that then recolonize freshwater stream ecosystems. Postlarvae have special adaptations that allow them to scale waterfalls that can be greater than 300 m in height, including gobies with pelvic fins fused into suction cups (Benbow et al. 2004a), shrimp with strong claws, and limpet-like snails with muscular feet (Benbow et al. 2004b, Brasher 1997, Gorbach et al. 2012, Kinzie 1993). Invertebrate biomass is dominated by two shrimp species (Resh and deSzalay 1995). Although present, aquatic insects have lower biomass and diversity than is typical in temperate continental streams, although this varies by insect species (Benbow 2008) and across flow conditions (Benbow et al. 2005; McIntosh et al. 2002, 2003). Some trophic guilds common in temperate streams are lacking, such as the shredding guild.

Geologic nutrient inputs—

Studies done outside of HETF have found geographic patterns of geologic and atmospheric inputs of nutrients within the Hawai'ian Islands that may affect nutrient loading to HETF streams. The weathering of parent material can contribute phosphorus (P) and silicate (SiO_4^{2-}), as well as other important dissolved nutrients, although contributions vary with substrate geologic age. For example, younger,

P-rich substrates can potentially provide more P to soil pore water, while older geologic substrate can provide more biologically fixed nitrogen (N) (Hedin et al. 2003, Vitousek and Farrington 1997). These patterns are not as apparent in stream water (Wiegner, n.d.), likely owing to other processes occurring within the ecosystem N cycle, such as plant uptake, denitrification, adsorption along flow paths through soils to streams, and uptake by stream organisms (Hedin et al. 2003; Wiegner et al. 2009, 2013).

Atmospheric nutrient inputs—

Atmospheric inputs are a second important source of nutrients to these watersheds. Fixed N and P are deposited from the atmosphere to land in rainfall, dust (or “dry”) deposition, and cloud or fog interception (Carrillo et al. 2002, Vitousek 2004).

Across the Hawai’ian Islands, atmospheric N contributions are dominated by cloud water inputs of ~5.8 kg N/ha/yr on the moist, windward side of islands, compared to biological N fixation of about 1.0 kg N/ha/yr which is more evenly distributed geographically (Vitousek 2004). Contributions of volcanically fixed N can significantly increase atmospheric deposition on volcanically active, young substrates where there are active lava flows and eruptive vents. For example, on volcanically active Hawai’i Island, total N deposition (inorganic and organic) over a 5- to 7-year period averaged 17 kg N/ha/yr, with more than 90 percent from fog interception and the rest from precipitation deposition. In contrast, N inputs from precipitation on volcanically inactive Kauai Island were only 0.2 kg N/ha/yr, although fog inputs were not measured (Carrillo et al. 2002). The high amount of N deposition on Hawai’i Island was due to thermal fixation of atmospheric N contacting erupting Kilauea lava flows (Huebert et al. 1999). When active lava flows enter seawater, aerosols can also locally increase P deposition fiftyfold in near-coast areas (Sansone et al. 2002).

Research History

In 2010, the Climate Change and Pacific Island Water Resources (CCPIWR) study was initiated by the USFS to use the North Hilo coast of Hawai’i Island as a study area to investigate how climate change will affect the ecological, hydrological, and biogeochemical function of tropical island streams. This region is well-suited as a location for a space-for-time substitution study across a rainfall gradient of 3500 mm/yr. Streams at the wetter end of the gradient represent current conditions in watersheds that provide much of the surface water for urban and agricultural areas of Hawai’i. Streams at the drier end of the gradient represent forecasted future conditions in those supply watersheds under scenarios of a drier climate.

As part of the CCPIWR study, long-term research sites were established in four streams within the LWF—Ka’awali’i, Kaiwilahilahi, Manowai’ōpae, and Pahale

streams, which are continually monitored for streamflow (fig. 18.1). An additional eight streams along the north Hilo coast, located outside of HETF, are also monitored by CCPIWR. The eight watersheds outside HETF are at the wet end of the rainfall gradient and drain watersheds with native-dominated forests and minimal human disturbance. Watersheds within HETF are at the dry end of the gradient but are otherwise similar to the other CCPIWR study basins in land cover and land use. Although Parham et al. (2008) classified all CCPIWR study streams as perennial, streams at the drier end of the gradient typically have zero flow during the May to October dry season and will be referred to here as intermittent (Hansen 2001). To minimize influences of geological age, all CCPIWR study streams were selected to be on geologic substrates less than 20,000 years old.

Prior to CCPIWR, several separate research projects had been done in these streams or watersheds. Michaud and Wiegner (2011) assessed nutrient fluxes in streams along the North Hilo coast. Fish surveys have been conducted by Hawai'i's Division of Aquatic Resources in the lower reaches of Ka'awali'i, Laupāhoehoe, Kilau, Manowai'ōpae, Kaiwilahilahi, Ha'akoa, and Pāhale streams that drain HETF (Parham et al. 2008). Fish surveys in the lower reaches of Manowai'ōpae and Kaiwilahilahi investigated how the invasion by nonnative poeciliid fish affected the ecological function of native streams (Holitzki et al. 2013). Forests along this coast were sites in the Long-term Soil Age Gradient study that examined shifts in nutrient limitation along a sequence of increasing geologic substrate age across the Hawai'ian islands (Hedin et al. 2003, Vitousek and Farrington 1997). Meteorological stations had been established in Manowai'ōpae and Ka'awali'i watersheds, which monitor air temperature, rainfall, and wind. Extensive surveys using LiDAR and hyperspectral remote sensing have documented forest structure, carbon stocks, and extent of invasive plants (Asner et al. 2008, 2011). Other studies have also examined how soil carbon stocks shift along temperature gradients within CCPIWR watersheds (Litton and Giardina 2008).

Availability of publications and data—

Since the establishment of HETF in 2007, nearly 100 papers have been published on studies that have examined the biogeochemistry, floral and faunal communities, and the impacts of invasive species and climate change. A complete list of reports and publications can be found online (USDA FS 2014, 2016). Streamflow, stream chemistry, and meteorological monitoring data are currently available upon request (MacKenzie and Giardina, n.d.). Atmospheric deposition data are available in Carrillo et al. (2002) and Vitousek (2004). Information on vegetation surveys, LiDAR, and other remote images can be found in Asner et al. (2005, 2008, 2011) or from Hughes (n.d.). For data from individual studies, contact publication lead authors.

Biological Responses to Stream Nutrients N and P

Issues of Concern

Freshwater is a critical resource for human communities on islands in Hawai'i and across the Pacific. Stream water is often used as drinking water as well as for recreation, traditional and cultural practices, irrigation for crops such as taro (*Colocasia esculenta* (L.) Schott), and for aesthetic values. Hiking to and swimming in streams and waterfalls is a popular activity that attracts tourists to many islands. Island streams also play an important role in maintaining the health of coastal marine ecosystems such as estuaries and coral reefs. Unfortunately, rapid population growth and land-cover change, including urbanization, intensive agriculture, and deforestation, have resulted in substantial harm to freshwater ecosystems and nearshore marine areas. These human activities on tropical islands have often decreased water quality through increased N, P, and sediment loading to streams (Bruland and MacKenzie 2010, Golbuu et al. 2003, MacKenzie 2008, Michaud and Wiegner 2011) that can also negatively affect nearshore waters, including coral reefs (Golbuu et al. 2007, 2011; Hoover 2002).

The increased spread of invasive plants and animals across islands of the western Pacific has severely affected N and P loading to Pacific Island streams. For example, N-fixing albizia trees (*Falcataria moluccana* (Miq.) Barneby & J.W. Grimes) can significantly increase N concentrations in streams through decomposition of N-rich leaf litter (MacKenzie et al. 2013) or from subsurface flows in albizia-invaded soils (Wiegner et al. 2013). Invasive poeciliid fish also increase the amount and forms of N and P in invaded streams (Holitzki et al. 2013). Feral ungulates, such as pigs (*Sus scrofa* L.), also degrade water quality through increased nutrient, sediment, and bacteria loading (Dunkell et al. 2011a, 2011b; Sidle et al. 2006; Singer et al. 1984; Strauch et al. 2016a).

Dams and diversions affect water quality in Hawai'i (Brasher 2003, McIntosh et al. 2002) and across the Pacific (Leberer and Nelson 2001). For example, nearly one-third of Hawai'i's perennial streams were diverted by the late 1970s (Assessment 1990, Parrish 1978) to support the sugar industry. Today, many of these diversions still function and reduce flow in downstream reaches. Lower flows result in warmer temperatures and lower dissolved oxygen (DO) levels (Benbow et al. 2005, Leberer and Nelson 2001, McIntosh et al. 2002) that can influence biogeochemical functions in stream water and sediments (Wiegner et al. 2009). Lower flows also increase residence time, breakdown, and remineralization of organic matter (Roberts et al. 2016), producing inputs of N and P to the water column. These impacts on water quality will likely be exacerbated in a warmer and drier climate.

Increased N, P, and sediment loading from land use and invasive species decreases water quality for drinking and recreation (e.g., Strauch et al. 2014). For example, Hilo Bay has one of the largest beaches on Hawai'i Island, but less than 10 percent of people using the beach in 2001 swam owing to water quality issues (USEPA 2002). Increased N and P loading can stimulate blooms of nonnative algae that replace native algae traditionally harvested for food by humans (Lapointe and Bedford 2011). Increased algal blooms can also decrease habitat for native stream and nearshore fish (MacKenzie 2008, Smith et al. 2001).

Climate models predict that Hawai'i will become warmer and drier during this century (Mimura et al. 2007). Detailed analyses predict that leeward coasts will show the strongest drying trends, while the trade wind-dominated windward coasts will experience no change or some drying. In contrast, Timm et al. (2013) predicted fewer heavy rainfall events, which would decrease flood frequency, but not necessarily increase the number of dry days. However, the absolute magnitude of changes in rainfall timing or intensity remains uncertain (Timm et al. 2015, 2016). Based on past trends during 1950–2007, rainfall intensity has generally increased across Hawai'i. Fewer yet more intense rainfall events occurred along with a general increase in number of dry days between rainfall events (Chu et al. 2010) and an increase in streamflow intermittence (Strauch et al. 2015).

Water quantity in streams is also threatened by high water use by invasive plant species (Strauch et al. 2016b) as well as continued withdrawal of stream water to support agriculture (Oki et al. 2010). Changes in rainfall patterns and corresponding shifts in streamflow regimes and flood frequencies would probably alter stream and nearshore habitat that support many species of native fish, shrimp, and snails that are traditionally harvested by many indigenous people in Hawai'i and across the Pacific (Atwood et al. 2012, Bell 1999, Couret 1976). Impacts of rainfall changes, invasive plants, and water diversions are only expected to be exacerbated by a warmer and drier climate. However, many details of how hydrological and ecological functions in tropical streams will respond to those changing climate or land use patterns are currently unknown.

Cross-Site and Regional Studies

Almost all stream studies at HETF have been done within the context of the cross-site CCPIWR study of 12 basins on the north Hilo coast of Hawai'i Island, rather than solely on streams within HETF.

Concentrations of dissolved and total (dissolved + particulate) N and P constituents were monitored in nine of the CCPIWR streams, including three located within LWF: Ka'awali'i, Manowai'ōpae, and Pāhale. Water samples were

grab-sampled from each stream once a month from June 2011 through August 2012, and analyzed for total carbon (C), N, and P nutrients and dissolved C, N, and P nutrients. For a complete description of methods used, see Wiegner et al. (2009) or Holitzki et al. (2013).

Total N (TN) was typically lower than total dissolved N, which included dissolved inorganic and organic N. This difference was attributed to microbial utilization of dissolved N that occurred in unfiltered TN samples prior to analysis (Mead 2012). This also suggests that N in our TN sample was largely in dissolved forms. Samples were collected during low flows when particulate concentrations would have been lowest, compared to stormflows that resuspend particles (Wiegner et al. 2009). Inorganic N, composed of the sum of nitrate (NO_3^-)-N and nitrite (NO_2^-)-N (referred to as ΣNO_3^-) plus ammonium (NH_4^+)-N, represented only 26.6 ± 9.8 percent standard deviation (SD) (range 16.3 to 48.8 percent) of the average monthly TN concentrations (table 18.1, fig. 18.2). The remainder of TN was primarily dissolved organic N, a complex mix of organic N compounds that have been little studied in HETF streams. Our measured concentrations of TN generally increased as flow decreased along the CCPIWR gradient when regressed against base (Q90), median (Q50), and stormflows (Q10) (table 18.2, fig. 18.2). This would have been significant if we had raised the alpha level to 0.1 and suggests that highest TN concentrations typically occurred in streams at the drier end of the CCPIWR gradient that had lower flows or were intermittent. Continued monitoring is needed to verify this pattern.

Total phosphorus (TP) was dominated by total dissolved phosphorus (TDP). TDP was strongly and negatively correlated to median streamflow (Q50) ($R = -0.73$, $p < 0.05$) and stormflows (Q10) ($R = -0.80$, $p < 0.01$) across the CCPIWR gradient. TP and TDP concentrations were generally higher in streams at the drier end of the CCPIWR gradient. In contrast, phosphate (PO_4^{3-}) was significantly and positively correlated to base (Q) ($R = 0.85$, $p < 0.01$) and median flows (Q50) ($R = 0.80$, $p < 0.01$), but not stormflows (Q10) across the CCPIWR gradient.

Hydrology has a strong influence on stream water quality as runoff and base-flow can dilute or increase the relative concentration of a nutrient, depending on its source. The negative correlations observed between N constituents, TP, and TDP and flow conditions along the CCPIWR gradient (table 18.2), as well as their higher concentrations in streams at the drier end of the gradient (figs. 18.2 and 18.3), were likely because of lower groundwater inputs, lower overall flow conditions, and resulting longer residence time of water. Lower groundwater inputs in streams at the drier end of the gradient did not dilute concentrations of N constituents, TP, and TDP. In contrast, streams at the wetter end of the gradient had higher groundwater

Table 18.1—Catchment area, flow metrics, and monthly average (± 1 standard deviation) nutrient concentrations for the nine streams sampled across the North Hilo Coast of Hawai'i Island^a

Stream	Area	Q90	Q50	Q10	ΣNO_3	PO_4^{3-}	SiO_4^{2-}	NH_4^+	TDP	TP	TDN	TN	DOC	TOC
Pāhale*	10.14	0.00	0.00	0.13	2.70 (4.67)	0.19 (0.18)	6.86 (8.32)	1.07 (1.23)	0.23 (0.33)	0.42 (0.61)	14.75 (7.38)	11.58 (4.91)	360.86 (106.71)	353.71 (88.98)
Manowai'ōpae*	3.84	0.00	0.00	0.00	0.59 (0.62)	0.15 (0.14)	15.90 (12.72)	1.43 (1.42)	0.37 (0.45)	0.58 (0.44)	12.32 (7.36)	11.66 (8.75)	396.60 (313.73)	395.35 (312.55)
Ka'awali'i*	33.10	0.01	0.03	0.03	2.61 (3.58)	0.16 (0.15)	23.59 (20.43)	1.59 (1.33)	0.26 (0.39)	0.35 (0.35)	13.51 (5.12)	11.23 (3.73)	247.73 (70.59)	246.56 (76.05)
Makahiloa	9.60	0.00	0.03	0.44	1.89 (2.56)	0.16 (0.15)	8.75 (8.76)	1.30 (1.31)	0.20 (0.34)	0.26 (0.34)	16.95 (16.29)	8.15 (3.40)	332.31 (148.84)	304.75 (115.50)
Pāhoehoe	1.30	0.03	0.05	0.13	2.43 (1.29)	0.17 (0.12)	40.94 (37.61)	1.05 (1.62)	0.20 (0.47)	0.15 (0.42)	7.14 (6.85)	4.91 (5.31)	107.58 (92.06)	107.57 (94.27)
'Uma'uma	74.43	0.10	0.33	4.57	1.72 (4.49)	0.17 (0.16)	21.09 (27.59)	1.27 (1.68)	0.12 (0.25)	0.08 (0.20)	11.45 (14.44)	6.47 (2.72)	319.81 (132.28)	305.67 (112.50)
Kapu'e	20.69	0.12	0.30	3.61	1.21 (1.82)	0.18 (0.14)	16.42 (23.11)	1.08 (1.34)	0.08 (0.21)	0.10 (0.21)	7.97 (6.38)	5.96 (4.82)	287.53 (92.07)	279.93 (80.45)
Kolekole	17.23	0.15	0.29	1.81	0.76 (1.21)	0.20 (0.16)	44.11 (63.90)	1.24 (1.40)	0.13 (0.27)	0.04 (0.16)	11.57 (10.60)	9.14 (8.11)	292.07 (149.40)	297.27 (147.50)
Honoli'i	30.36	0.40	0.71	3.51	1.23 (1.69)	0.23 (0.12)	60.00 (60.52)	0.96 (1.69)	0.10 (0.21)	0.14 (0.29)	8.06 (7.94)	5.05 (5.29)	207.63 (64.87)	189.87 (68.84)

Nutrients measured monthly from June 2011 through August 2012 are in millimoles per liter and include sum nitrate and nitrite (ΣNO_3), phosphate (PO_4^{3-}), silicate (SiO_4^{2-}), ammonium (NH_4^+), total dissolved phosphorus (TDP), total phosphorus (TP), total dissolved nitrogen (TDN), total nitrogen (TN), dissolved organic carbon (DOC), and total organic carbon (TOC). Ka'awali'i, * Pāhale, and Manowai'ōpae streams are three streams that drain the Laupāhoehoe Wet Forest unit of the HETF, while the remaining six streams are located along or rainfall gradient on the North Hilo Coast of Hawai'i Island.

^a Catchment area is in square kilometers and represents that area above the study reach. Flow metrics include baseflow (Q90), medianflow (Q50), and stormflow (Q10) in units of cubic meters per second.

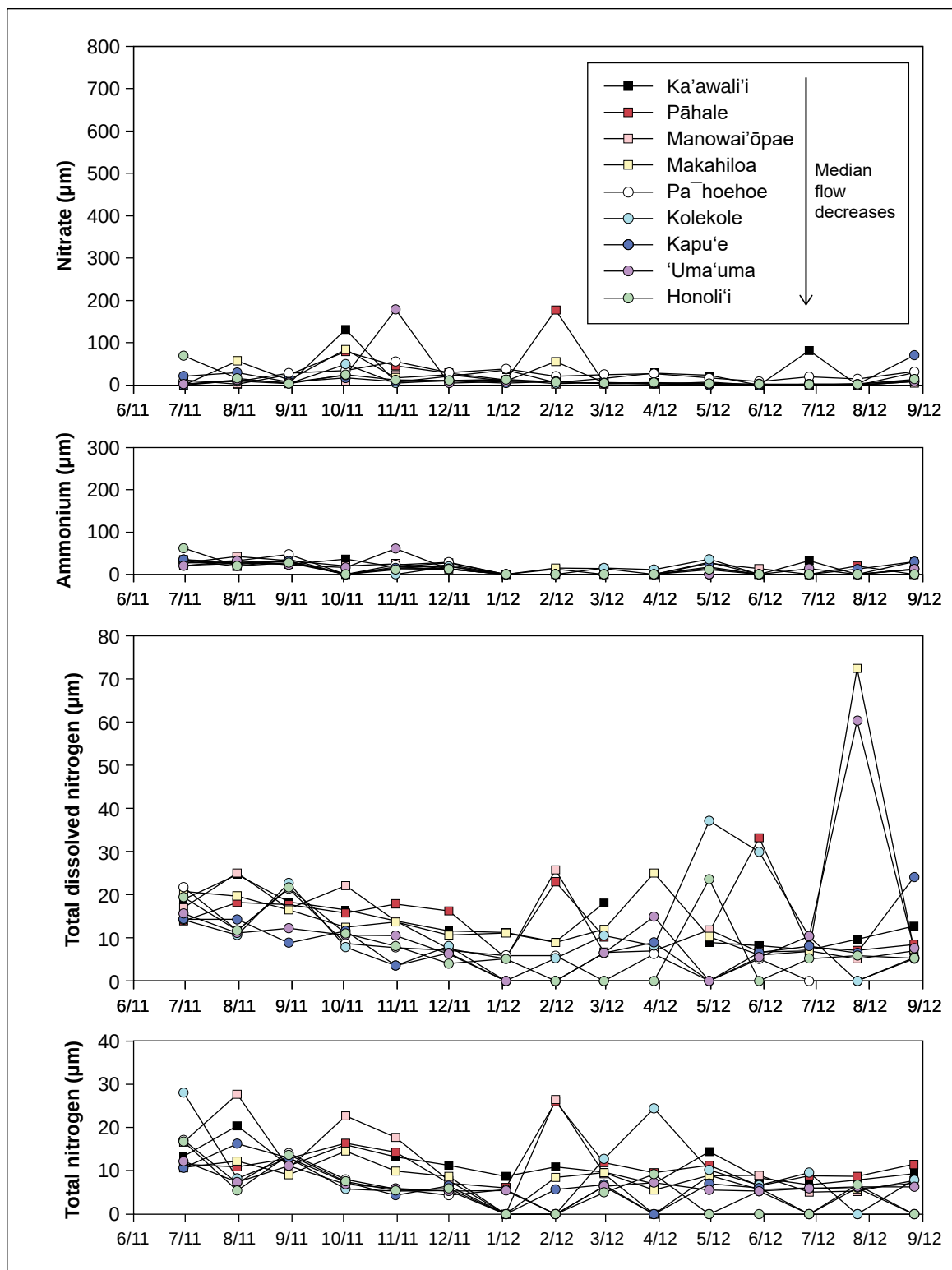


Table 18.2—Results from Pearson's Product Moment correlation between various streamflow metrics across the Climate Change and Pacific Island Water Resources gradient, and monthly nutrient^a concentrations averaged across the 13 months they were sampled

Nutrient ^a	Q90	Q50	Q10
ΣNO_3	-0.41	-0.43	-0.38
PO_4^{3-}	0.85**	0.80**	0.48
SiO_4^{2-}	0.77*	0.71*	0.31
NH_4^+	-0.56	-0.52	-0.39
TDP	-0.64	-0.73*	-0.80**
TP	-0.54	-0.63	-0.70*
TDN	-0.56	-0.55	-0.47
TN	-0.58	-0.63	-0.63
DOC	-0.34	-0.28	-0.05
TOC	-0.37	-0.31	-0.09

* = $p < 0.05$

** = $p < 0.01$

Q90 is low flow, Q50 is median flow, and Q10 is high flow.

^a Nutrients include sum nitrate and nitrite (ΣNO_3), phosphate (PO_4^{3-}), silicate (SiO_4^{2-}), ammonium (NH_4^+), total dissolved phosphorus (TDP), total phosphorus (TP), total dissolved nitrogen (TDN), total nitrogen (TN), dissolved organic carbon (DOC), and total organic carbon (TOC).

inputs that diluted N concentrations (Strauch et al. 2017). Lower flows in streams at the dry end of the rainfall gradient also had longer stream water residence times. As a result, particulate organic matter in these streams have more time to break down, as opposed to being flushed downstream to the ocean (Roberts et al. 2016). Thus, the greater breakdown of particulate organic matter in streams at the drier end of the gradient may also contribute to the higher concentrations of N, TP, and TDP observed there (MacKenzie et al. 2013).

Rock weathering has been hypothesized as one potential explanation for increased concentrations of PO_4^{3-} with increased base- and median flows in streams along the CCPIWR gradient. The streams sampled within the LWF were from watersheds with geologic substrate of comparable age to the other watersheds in the CCPIWR study. Although the relatively young substrates in all these watersheds produce soils high in PO_4^{3-} , but low in N (Vitousek et al. 2009), the streams at the drier end of the gradient received less rainfall, which would have hypothetically slowed weathering rates of this P-rich rock. This could have contributed to lower stream water PO_4^{3-} concentration in drier watersheds. Another contributing factor to lower PO_4^{3-} concentrations in streams with lower Q90 and Q50 at the drier end of the gradient may be decreased groundwater inputs (Strauch et al. 2017), which is an important source of rock-derived PO_4^{3-} (Wiegner et al. 2009).

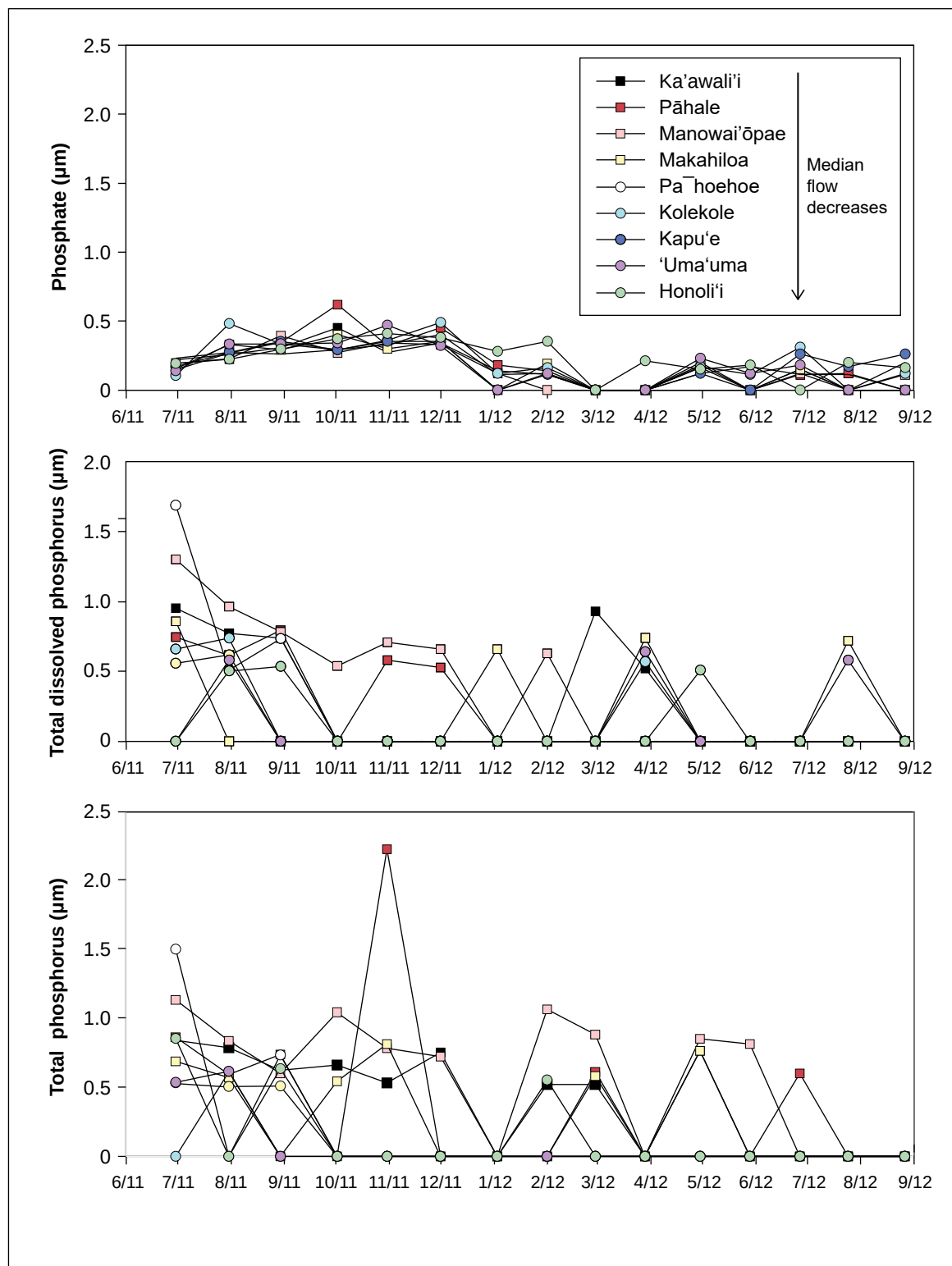


Figure 18.3—Monthly concentrations of phosphorus constituents measured from June 2011 through August 2012.

Biological activity is also probably influencing concentrations of nutrients in streams at the drier end of the gradient. Results of a nutrient spiraling study of streams across the CCPIWR rainfall gradient provide evidence that biological processes in these stream ecosystems may be limited by stream water N and P concentrations and that limitation of both nutrients may change with flow. This study used nutrient additions to measure the amount of N and P taken up by stream biota that include algae, submerged macrophytes, and microbes. Preliminary results revealed that demand for N ($48.8 \text{ mg N/m}^2/\text{day}$) and P ($37.0 \text{ mg P/m}^2/\text{day}$) did not vary much among perennial streams at the wetter end of the gradient (Frauendorf et al. 2019). However, in intermittent streams at the drier end of the gradient, the demand for N and P was reduced by about half and resulted in lower uptake of both these nutrients. Wiegner et al. (2013) found similar N vs. P limitation in Ainako Stream, elsewhere on Hawai'i Island. Benthic algal biomass was significantly greater on plates inoculated with both N and P than on plates inoculated with only N, only P, or uninoculated controls. While Ainako Stream differs from the CCPIWR streams because it is spring fed and on older geologic substrate, these results provide more evidence that both N and P together are limiting nutrients in perennial streams on Hawai'i Island.

A preliminary study of benthic biofilm in three CCPIWR study streams found standing stocks of benthic biofilm biomass were lower in streams at the drier end of the rainfall gradient with lower baseflows. Biofilm consist of interacting communities of autotrophs, such as diatoms and filamentous algae, and heterotrophs, such as fungi, protozoans, and bacteria. Biofilm biomass was measured as chlorophyll *a* (chl *a*, mg/m^2) and ash-free dry mass (mg/m^2) that grew on an initially bare substrate that was exposed in the stream for a known period of time. Biofilm biomass was lowest in the two streams at the drier end of the gradient that had overall lower flows than the stream at the wetter end of the gradient (Foulk et al. 2012) (fig. 18.4). In another study, benthic algal productivity, measured as chl *a* once a month for 12 months, was also significantly lower in streams at the drier end of the gradient with lower streamflows ($r^2 = 0.91$, $p < 0.05$) in four CCPIWR study streams (Frauendorf et al. 2019). Lower biofilm biomass in lower flow and intermittent streams may be due to P-limitation at low flows, or nutrient uptake may be reduced in lower streamflows owing to a greater diffusive boundary layer for benthic algae (Finlay 2004). Regardless of the causal mechanism, patterns of benthic biofilm biomass have important implications for stream food webs, because biofilm is a major food resource for consumers, including native assemblages of shrimp, snails, gobies, and aquatic insects (Benbow et al. 2005, Brasher 1997, Kido 1996, Riney 2015). For example, benthic algae makes up 50 to 80 percent of shrimp (*Atyoida bisulcata*) diets in streams along the CCPIWR rainfall gradient (Riney 2015). A decrease in

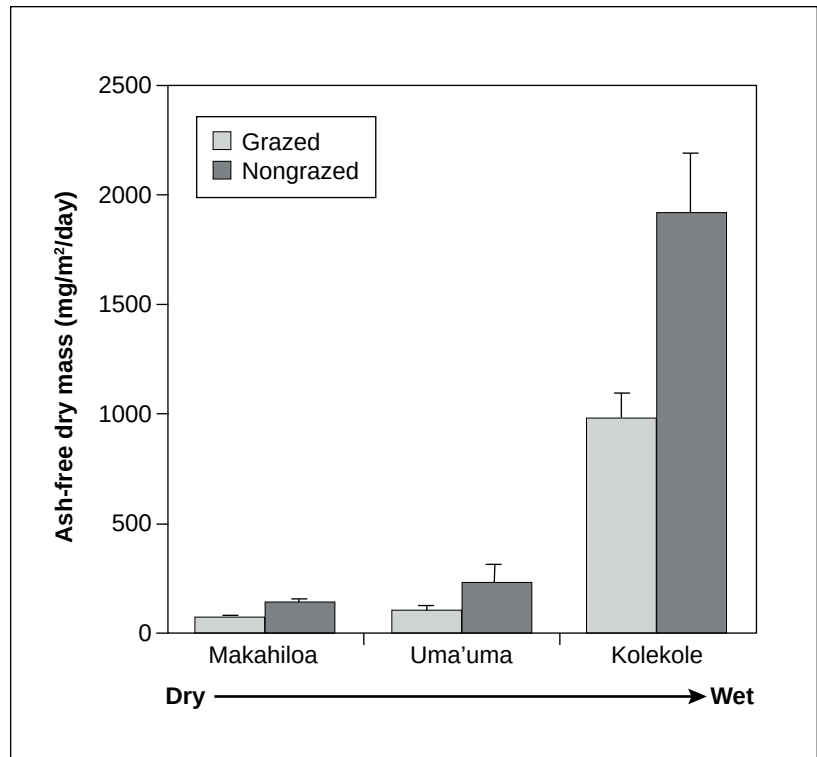


Figure 18.4—Ash-free dry mass (AFDM; $\text{mg/m}^2/\text{d}$) of periphyton collected from grazed and nongrazed plates in streams across the Climate Change and Pacific Island Water Resources study rainfall gradient. Grazed AFDM is significantly different in the Kolekole stream, located at the wet end of the gradient, but not different in the Uma'uma (UMA) or Makahiloa streams at the drier end of the gradient. Grazed and nongrazed AFDM plates are only different from each other in the Kolekole stream. Reproduced with permission from Foulk et al. (2012).

shrimp density, size, and body condition in streams at the drier end of the gradient may be explained, in part, by decreased benthic algal biomass in lower flow streams (Tingley 2017).

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

Streamflow has been continuously monitored with stream gages that were installed by the USFS in 2010–2011 in 11 of the 12 CCPIWR basins, including three streams within HETF. The stream gage in the 12th stream, Honoli'i, was installed and has been maintained by U.S. Geological Survey since 1911 (station 16717000). The recently installed gages were sited in stable reaches, and no changes have been observed in streambed conditions over 4 to 5 years (Gore 2007, Turnipseed and Sauer 2010).

Rainfall and air temperatures have been monitored across the CCPIWR watersheds since 2011. Comparing watersheds across the rainfall gradient, as mean annual rainfall (MAR) decreased, relative rainfall intensity (maximum daily

rainfall/median daily rainfall) increased, and days with zero rainfall increased, streams had more days with zero flow, and baseflow receded more quickly to no flow between rains. Low, median, and high streamflows as well as flashiness (frequency of stormflows exceeding two times that of Q50) and flow stability (Q90:Q50) all increased with increasing MAR. Flow variability (Q10:Q90) decreased with increasing MAR. This suggests that if MAR decreases with climate warming, streamflow in Hawai'ian watersheds will decrease and become less stable and flashier. These expected changes in flow conditions with warming climate have implications for the reliability of water supply to downstream users and for the quality of habitat for aquatic organisms, including the amphidromous fish and invertebrates that dominate these streams (Strauch et al. 2015).

Dose-Response Studies

Studies of dose response to N and P are currently underway in streams draining the LWF as part of the CCPIWR study, but results are not yet available. Nutrient demand is being measured using nutrient injections of NH_4^+ , NO_3^- , and PO_4^{3-} into streams, along with a conservative tracer of sodium chloride (Covino et al. 2010). The study is examining how shifts in streamflow affect ecosystem nutrient demand, consisting of the amount of dissolved N and P required by a defined area of the benthos, and the proportion of the aquatic ecosystem demand that is supplied through remineralization by dominant stream taxa, including shrimp, caddisflies (*Cheumatopsyche analis*), and various species of chironomids.

Reference Watersheds

As conservation lands, the seven major watersheds in the LWF are currently managed for minimal onsite human disturbance and will remain in that status in perpetuity. Streamflow from four of these reference watersheds, Ka'awali'i (1420 ha), Manowai'ōpae (100 ha), Kaiwilahilahi (1510 ha), and Pahale streams (1000 ha) (fig. 18.1), have been monitored since 2011. Permanent forest monitoring plots and a climate monitoring tower are also located within these reference watersheds (Inman-Narahari et al. 2010, Litton et al. 2011).

Intact native Hawai'ian forests make up 60.8 percent (range 43 to 77 percent) of vegetative cover on LWF reference watersheds (Parham et al. 2008). Like other remaining native Hawai'ian forests, vegetation is dominated by native 'ōhi'a and koa forest (Asner et al. 2005). Legacies of past land use that persist in small portions of these watersheds include nonnative tropical ash (*Fraxinus uhdei* (Wenz.) Lingelsh) and eucalyptus (*Eucalyptus* spp.) plantations and, at lower elevations, abandoned sugarcane fields now dominated by invasive strawberry guava or managed as pasture. Feral pigs are common in the reference watersheds (Maly and Maly

2006).

These forests were and continue to be considered sacred to native Hawai'ians. Traditionally, they cautiously collected resources such as wood, other plant materials, and birds, and probably had minimal impacts on soil and vegetation. Since Western contact, the upland sections of these watersheds were grazed by domestic sheep and cows, and koa trees were selectively harvested, but these practices were discontinued when the state granted these lands conservation status. Collection of culturally important plants and hunting are currently permitted in these watersheds (Maly and Maly 2006).

Responses to Management and Natural Disturbances

Streams draining LWF were part of a larger study by Holitzki et al. (2013) that quantified disturbances caused by introduced invasive fish in six streams with similar land use histories, including the lower reaches of Kaiwilahilahi and Manowai'ōpae streams, downstream of HETF. Average ΣNO_3 , TN, and total organic carbon (TOC) yields were eight, six, and five times higher, respectively, in three streams invaded by poeciliid fish compared to poeciliid-free streams dominated by native species. Benthic biofilm ash-free dry mass was 1.5 times greater in poeciliid-invaded streams, which may have been related to the higher levels of N in these streams.

Invasive plants with associated N-fixing bacteria can also contribute dissolved nutrients to Hawai'ian streams. For example, leaf litter breakdown from the invasive N-fixing albizia tree can significantly increase stream water concentrations of $\text{NO}_3^- + \text{NO}_2^-$ (MacKenzie et al. 2013, Wiegner et al. 2013).

A study by Strauch et al. (2016b) modeled streamflow under various climate change and invasive species-spread disturbance scenarios in 88 watersheds across Hawai'i, including all watersheds in the LWF. Decreases in base-flow yield (Q90Y) and stormflow yield (Q10Y) in response to declines in annual rainfall dwarfed effects of projected temperature increase or exotic plant species invasion. Wetter watersheds had greater annual flow reductions than currently drier ones. Effects of decreased MAR were accentuated when combined with strawberry guava invasion and warming temperature. Modeling management to restore invaded forests by removing all strawberry guava reduced the impacts of climate change on streamflow. The study concluded that, while potential changes in precipitation from climate change in the Hawai'ian Islands are likely to exert significant impacts on streamflow, managing invasive vegetation might provide strong mitigating benefits (Povak et al. 2017).

Reliability and Limitations of Findings

Results from HETF probably apply to other watersheds on the windward sides of Hawai'i, Maui, or Molokai Islands that have similar climate, geology, geological age, and land use history. In areas that are dissimilar to HETF, or where a high degree of accuracy is required, it might be beneficial to consider validation studies or monitoring to test how well HETF results predict local conditions.

Research Needs

The research needs of highest priority to the water quality regulatory community related to N and P that could be filled at HETF include: additional detailed measurements of the composition of the aquatic biological communities in reference streams under natural background conditions, and identification of the threshold levels and response times of these communities to increased stream water N and P. Filling this gap would be important to the regulatory community because it would provide science-based data that could be used by Hawai'i's Commission on Water Resources Management and the Clean Water Branch of the Department of Public Health to develop water quality standards and land management regulations that protect the integrity of intact aquatic ecosystems. Filling that need at HETF would require future research that included continued monitoring of nutrients in stream waters and performing regularly repeated stream surveys of reference stream biological communities, including benthic algal biofilm, macrophytes, macroinvertebrates, and vertebrates. Studies to identify threshold levels would also be required using increased stream N and P to elicit significant biological responses. Such studies would include comparing HETF streams to otherwise similar streams that have higher nutrient levels, and studies of biological responses to controlled nutrient additions of N and P, together and separately, in stream reaches and in artificial stream microcosms.

Other research needs of the regulatory community, but of lower priority, that might be addressed at HETF include the following:

- How do climate change, land use, and invasive species interact to affect water quality and quantity in Hawai'i and Pacific Island streams?
- How does changing climate influence water availability through changes in groundwater recharge and surface water-groundwater interactions, and alter flood risk, especially for low-lying coastal areas?
- How does nutrient spiraling determine the fate of nutrients in Pacific Island streams, including the sources and sinks of these nutrients along a stream continuum?
- What explains differences in nutrient levels between soil pore water and stream water across geologic substrates of differing age?
- How do native fish and invertebrate assemblages in Hawai'ian streams alter nutrient dynamics and affect the algal food base?

Potential Utility to Water Quality Regulatory Agencies

Existing monitoring datasets from the HETF and the CCPIWR research platform might be useful to the regulatory community as baseline data to help identify impaired waters under section 303(d) of the Clean Water Act of 1977 (33 U.S.C. s/s 1251 et seq.) by providing data on stream conditions in relatively undisturbed Hawai'ian headwater streams, or as a baseline for assessing impacts on streams of land use change and invasive species. Data can also be used for the development of total daily maximum load (TMDL) source assessments for Hawai'i. These data might also be used by regulators to set guidelines for restoration and conservation of impaired waters to increase the resilience of these watersheds to stressors and improve their capacity to provide clean and plentiful water for the humans, plants, and sensitive Hawai'ian stream and nearshore ecosystems.

Key points:

- The CCPIWR monitoring network has found relationships between measurements of stream water concentrations of P and total N and flow that suggest there are hydrologic, geologic, and biological processes that influence stream nutrients.
- In streams with perennial flows, initial results indicate that stream water N and P together limit aquatic biological communities, but with intermittent flow in streams at the drier end of the CCPIWR gradient, demand for both N and P declined by nearly half, and biofilm biomass production may be both N and P limited.
- Maintaining native-dominated forests or restoring degraded ones to native-dominated forests have potential to mitigate climate change impacts on water quantity and quality of Hawai'ian streams.
- The highest priority research need of the regulatory community that could be filled at HETF includes continued water quality monitoring, detailed surveys of aquatic biological communities, and studies to identify thresholds of N and P enrichment that elicit biological responses in these stream communities.
- Existing datasets and research results from HETF and the regional CCPIWR study have strong potential to be useful to regulatory agencies as a scientific base for developing regulations that protect beneficial uses of Hawai'ian streams and nearshore waters.

Biological Responses to Stream Nutrients Other Than N and P

To date, the nutrients other than N and P that have been studied in HETF streams have been SiO_4^{2-} , dissolved organic carbon (DOC), TOC, and dissolved organic matter (DOM).

Issues of Concern

There are no major water quality issues related to nutrients other than N and P in Hawai'i. Diatoms that are an important component of benthic biofilms require SiO_4^{2-} as a nutrient. Silicate is also useful as a tracer for groundwater. DOC is a concern in Hawai'ian streams. Although it is not a nutrient for the purposes of this report, DOC is an energy source for aquatic food webs, and, in excess, can degrade water quality by stimulating heterotrophic respiration and depressing DO in water bodies (Atwood et al. 2010, Johnson and Wiegner 2014, Larned et al. 2008). Increased urban development and agriculture can increase the bioavailability of DOC (Seitzinger et al. 2002, Wiegner and Seitzinger 2004), and changes in stream-flow from climate warming, stream water withdrawals, and their combination may also affect future loads of bioavailable DOC in Hawai'ian streams.

Cross-Site and Regional Studies

Silicate is a nutrient that is monitored in the streams of the CCPIWR study. Measured SiO_4^{2-} concentrations were generally higher in higher flow CCPIWR streams and were strongly and positively correlated to baseflows (see table 18.2). Silicate is a product of rock weathering, similar to PO_4^{3-} . The positive correlation of SiO_2^{2-} with baseflow across the CCPIWR gradient may indicate lower rates of rock weathering of SiO_2^{2-} in basins with drier climates or smaller groundwater inputs.

Silicate concentrations from CCPIWR (range 6.86 to 60 mmol/L) (table 18.1, fig. 18.5) were at the lower end of the global range reported for streams and rivers (range 8.9 to 320 mmol/L) (Fulweiler and Nixon 2005, Li et al. 2007, MacKenzie 2008, Turner et al. 2003). Because SiO_4^{2-} dissolution is temperature dependent, concentrations of dissolved silicate are usually higher in tropical than in temperate streams (Turner et al. 2003). Derry et al. (2005) reported that the lower concentrations in Hawai'ian streams compared to other tropical systems were likely due to biological uptake of SiO_2^{2-} by diatoms.

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

Dissolved organic matter—

The measured average ($\pm$ SD) TOC concentration across all streams (275.6 ± 86.0 mmol/L, range 107.6 to 395.4 mmol/L) was typically lower than the average DOC (283.6 ± 87.0 mmol/L, range 107.6 to 396.6 mmol/L) (fig. 18.5, table 18.1). Similar to N, this was attributed to microbial utilization of DOC that occurred in the unfiltered TOC samples prior to sample analysis (Mead 2012). TOC showed no apparent patterns with flow and was largely composed of DOC. Factors that control DOM concentrations in Hawai'ian streams are not well understood. DOM sources to Pacific Island streams likely include soil pore water, leaf litter leachate, and benthic algae exudates (MacKenzie 2008, Wiegner et al. 2009), but how these sources result in observed stream DOC concentrations is not currently known. Michaud and Wiegner (2011) found that DOM in Hawai'ian streams was generally not correlated to MAR, human population density, or percentage of agricultural land. Similarly, modeling C fluxes from lotic systems across the main Hawai'ian Islands did not explain stream DOC concentrations (MacKenzie et al. 2017).

Dose-Response Studies

Dose-response studies for nutrients other than N and P have not been conducted at HETF.

Reference Reaches

SiO_4^{2-} , DOC, and TOC were monitored monthly from June 2011 to August 2012 in the three streams draining HETF reference watersheds (table 18.1).

Responses to Management and Natural Disturbances

There have been no studies at HETF for nutrients, other than N and P, or studies of DOM in response to management or natural disturbances.

Reliability and Limitations of Findings

Results of studies of nutrients other than N and P from HETF probably apply to other watersheds on the windward sides of Hawai'i, Maui, and Molokai Islands that have similar climate, geology, geological age, and land use history. In areas that are dissimilar to HETF, or where a high degree of accuracy is required, we suggest considering validation studies or monitoring to test how well HETF results predict local conditions.

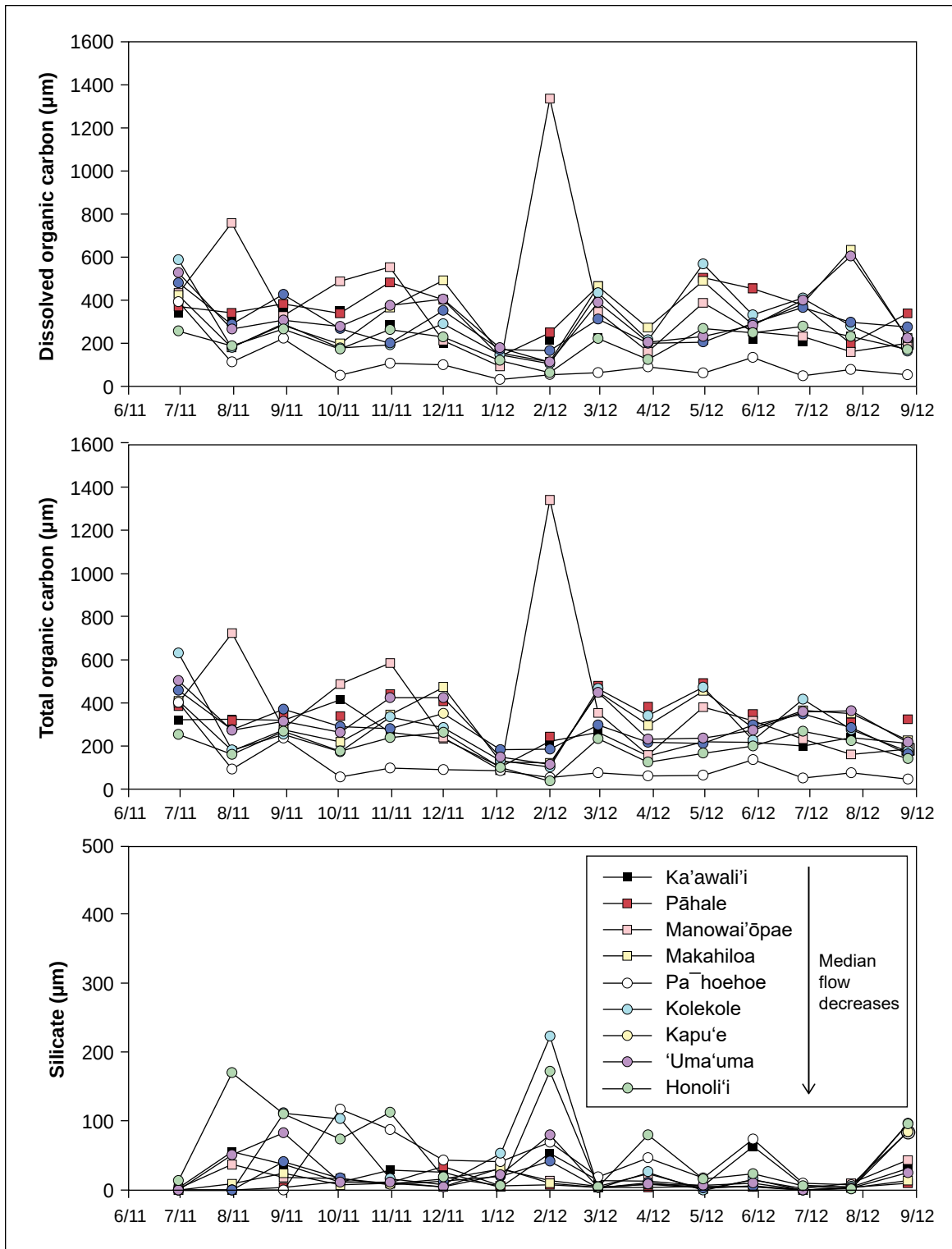


Figure 18.5—Monthly concentrations of carbon constituents and silicate measured in streams across the Climate Change and Pacific Island Water Resources study stream flow gradient from June 2011 until August 2012.

Research Needs

The research need of highest priority to the regulatory community, related to nutrients other than N and P, that could be filled at HETF would be a better understanding of carbon processing in tropical island streams, especially more detailed information on the sources and fate of dissolved inorganic and organic C and particulate organic C in undisturbed Hawai'ian headwater streams, both perennial and intermittent. These carbon sources drive important metabolic processes in streams and nearshore waters (MacKenzie et al. 2017). A better understanding of the sources, the dynamics, and processes that control these C constituents would help regulatory agencies to develop more effective rules for the management of DOC loading in Hawai'ian watersheds to protect beneficial uses of these waters. More scientific understanding of DOC dynamics in relatively undisturbed headwaters might be particularly useful as a baseline for assessing impacts of development in more disturbed streams. Filling this research need at HETF would require continued monitoring of LWF streams for DOC and total C (dissolved + particulate), turbidity, as well as additional studies to distinguish between labile and recalcitrant forms of DOC in stream water. In addition, process-oriented studies would be needed to investigate what processes control stream water DOC, including sources of stream C, such as instream vs. surface runoff vs. groundwater, and sinks of C, such as stream metabolism and volatilization. The intermittent streams in LWF in the drier parts of the rainfall gradient have potential to be especially useful for understanding whether processes controlling DOC in intermittent streams are different from controls in perennial streams.

Another research need of regulatory agencies that might be addressed at HETF, although of lower priority, would be to study how land use change and invasive plants and animals affect sediment inputs and retention times within flashy Hawai'ian streams.

Potential Utility to Water Quality Regulatory Agencies

Existing datasets from HETF and the CCPIWR study on background levels of sediment and nutrients other than N and P from undisturbed reference watersheds and their hydrologic response to intense rainfall events might be used by regulatory agencies to model what amounts of these constituents streams carry into estuarine and nearshore environments under natural conditions. Such information about water quality in undisturbed Hawai'ian streams might be helpful for developing enforceable, science-based TMDL limits.

Key points:

- Nutrients other than N and P are not currently associated with water quality concerns in this region.
- DOC provides an important energy source that supports culturally and economically important fisheries, but, in excess, can degrade water quality.
- Sources, sinks, and composition of stream DOC are not currently well understood in Hawai'ian streams.
- The highest priority research need of regulatory agencies not directly related to N and P that might be filled at HTEF is a better understanding of the sources, sinks, and composition of DOM in Hawai'ian streams under reference conditions.

Overview and Synthesis

The HETF is a newly established experimental forest that contains four watersheds that are part of the regional CCPIWR study. The concept behind the wider study is that streams in drier watersheds might predict hydrological, biogeochemical, and ecological responses of streams in wetter watersheds that are currently important water resources for Hawai'i, if the climate becomes drier under the influence of climate change. This information also provides insight into how reduced water quantity from invasive plant species or water withdrawals will affect Hawai'ian streams. This research has potential to benefit the water quality regulatory community by providing a scientific basis for anticipating how future climate or land use conditions may affect stream water quantity and quality and aquatic biotic communities in the streams of Hawai'i. This science is likely to be useful for developing regulations and management that will increase the resilience of Pacific Island streams and watersheds that are subject to these stressors.

Monitored watersheds in HETF represent reference conditions in headwater basins dominated primarily by undisturbed native forests at the drier end of the regional rainfall gradient. These sites provide regulators with measures of stream conditions under nearly pristine conditions that may serve as a natural baseline for developing water quality criteria and for TMDL modeling.

Important research results from the regional study suggest that aquatic communities in Hawai'ian headwater streams may be limited by both N and P in high rainfall areas with higher flows and that N and P demand is reduced in streams in drier areas with lower flows. Lower benthic algal biomass measured in streams in low rainfall basins may suggest P limitation of biofilms in these streams and explain the smaller body size and reproduction of native shrimp, a dominant macro-invertebrate in these headwater streams. Existing datasets on stream hydrology and stream water nutrients are potentially useful to regulatory agencies for setting water quality standards for nutrients.

Research needs of highest priority for regulatory agencies that might be filled at HETF were identified as studies of aquatic biotic communities in reference streams and threshold levels of stream nutrient enrichment that elicit significant responses in those communities, along with investigations of the sources and fates of dissolved organic and inorganic carbon compounds in HETF streams.

Results from HETF and the wider CCPIWR study are of scientific importance because their findings have potential to be applicable to streams with similar watershed characteristics, such as substrate geological age, rainfall, and elevation, found across the Hawai'ian Island chain and other mountainous islands of the tropical Pacific. Other potentially interesting scientific outcomes might also arise if cross-comparisons were made between HETF and the studies of the rainforest watersheds at Luquillo Experimental Forest (chapter 17) on Puerto Rico, another mountainous, tropical island with analogous though different aquatic species and land uses.

Key points:

- HETF is part of the long-term, regional CCPIWR study investigating the potential impacts of climate change on streams that are important sources of surface water for human populations and natural ecosystems on the north Hilo coast of Hawai'i Island.
- CCPIWR focuses on stream water quantity and quality, including stream nutrient levels, and aquatic biological communities composed of many species endemic to the Hawai'ian Islands.
- Effects of exotic invasive plants and animals and urban development are also under investigation.
- Research needs of highest priority to regulatory agencies that might be filled at HETF were identified as a better understanding of aquatic biotic communities in undisturbed reference streams and their responses to increased nutrient levels, and a characterization of the composition, sources, and fates of DOC in streams.
- Existing datasets and research results from HETF and the CCPIWR study have strong potential to be useful to regulatory agencies for developing regulations and programs to better protect beneficial uses of streams and nearshore marine ecosystems in Hawai'i and other mountainous tropical islands.

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Chapter 19: An Overview and a National Perspective

Douglas F. Ryan and Robert J. Danehy¹

Introduction

Chapters 2 through 19 of this report describe existing research results and monitoring datasets from individual experimental forests and ranges (EFRs) of potential use to water quality regulatory agencies. Research addressing the focus question of biological responses to stream nutrients differs among the reviewed EFRs. For example, all of the reviewed EFRs have studies that might be useful for the reference waterbody approach for developing nutrient criteria, while only some of those EFRs have results that would be applicable to the stressor-response modeling approach. In addition, the EFRs reviewed in this synthesis had science or monitoring products of broader interest to regulatory agencies that go beyond the focus question. Important but unfilled research needs of regulatory agencies were identified, and these could be addressed by future research studies at individual EFRs. Research networks, composed of multiple EFRs, have the potential to be used for addressing science needs of regulatory agencies at multiregional or national scales.

Existing EFR Research Relevant to the Focus Question Conditions in EFR Reference Streams

All of the EFRs reviewed in this synthesis have research results and monitoring datasets that might be useful for developing water quality criteria with the reference waterbody approach. They have relatively undisturbed streams in which stream nutrient concentrations and flow have been monitored. Data from these streams may be used to assess how proposed nutrient criteria compare with nutrient loads in reference streams. For example, Ice and Binkley (2003) compared nutrient levels in forested reference streams with ecoregional water quality criteria proposed by the U.S. Environmental Protection Agency (EPA). They found that ambient levels of nutrients in three streams in unmanaged basins, including reference streams in two EFRs reviewed in this report, exceeded the proposed criteria and would have been identified as impaired. Citing this evidence, they suggested that finer scale tools were needed that would more precisely reflect water quality patterns to develop nutrient criteria that were rational, achievable, and biologically relevant.

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Most of the EFRs reviewed in this report also have studies or surveys that provide data on aquatic biological communities in monitored, reference-stream conditions. Regulatory agencies need such data for developing regionally applicable biological indicators for assessing biological condition and developing biological criteria. The Fraser (chapter 9) and San Dimas (chapter 16) Experimental Forests (EFs) are exceptions because they lack aquatic biological surveys, although flow and nutrients have been monitored in their reference streams.

Also of potential regulatory interest, trend analyses of water quality have shown that nutrient concentrations in EFR reference streams in several parts of the country have significantly changed during recent decades (Argerich et al. 2013). The causes of these trends, and how widespread they are in their respective ecoregions, are currently under investigation. These findings are scientific evidence that baseline stream nutrient conditions can be dynamic, even in reference basins where onsite human activities have been carefully minimized. Such data from EFRs have strong potential to be useful to water quality regulatory agencies for addressing an important emerging question of how to set water quality criteria in an environment where “baseline” reference conditions are not constant but may be changing under the influence of regional- and global-scale drivers such as air pollution and changing climate. Thus, long-term monitoring data and ecological study results from EFR reference watersheds may be useful to the regulatory community for developing water quality criteria using the reference reach approach. Such monitoring may also be a potential source of data for addressing the emerging question of how to set water quality criteria in a changing world, where stream conditions, even in reference basins, cannot be assumed to remain constant.

Studies of Nutrient Stressor Responses at EFRs

Research and monitoring that may be useful to regulatory agencies for developing nutrient stressor-response models have been performed at eight of the reviewed EFRs: Coweeta Hydrologic Laboratory (HL) (chapter 14); Hubbard Brook (chapter 3), H.J. Andrews (chapter 5), Luquillo (chapter 17), Marcell (chapter 2), and Fraser EFs; Olympic Experimental State Forest (ESF) (chapter 12), and Hawai'i Experimental Tropical Forest (ETF) (chapter 18). Studies at these sites have investigated responses of various components of the stream biological community to gradients of stream nutrient concentration either imposed experimentally or among streams with different ambient nutrient levels.

Nutrient stressor responses has been investigated in the greatest depth at Coweeta HL. Short-term nutrient additions and bioassays of stream nutrient limitations have been performed there, but most remarkable have been studies

of biological responses to long-term chronic nutrient additions to streams lasting up to 5 years. These studies at Coweeta HL have examined nutrient enrichment effects throughout stream food webs, including effects on primary producers such as algae, heterotrophic decomposers such as bacteria and fungi, detrital biomass and respiration, and effects on higher trophic levels, including stream benthic macroinvertebrates and vertebrates. Effects of inputs of riparian plant litter to the detritus-based food webs in these streams have also been investigated with litter exclusion and addition experiments. Among the findings were evidence that responses to nutrient additions differed among trophic levels, and that some effects of chronic nutrient additions did not emerge until after 3 years or longer of continuous enrichment. In addition, studies found that stream detritus standing crop was decreased by nutrient additions, which altered the seasonal energy flows through food webs. The deep and broad understanding of the complexities of biotic responses to nutrients produced by the research at Coweeta HL is rare among stream studies nationwide.

At Hubbard Brook EF, nutrient limitation has been investigated using bioassays and short-term nutrient additions to whole streams. Nutrient additions of both nitrogen (N) and phosphorus (P), continued over 9 weeks, found that stream fungal production and respiration increased, but secondary production was unaffected. Trace additions of N and P were strongly taken up from stream water by biotic processes, additions of dissolved organic matter (DOM) decreased stream nitrate (NO_3^-), and removals of instream large wood increased P uptake from stream water. At H.J. Andrews EF, short-term nutrient additions found that NO_3^- was quickly taken up from the water column, but multiyear N additions to the stream had little effect on secondary trophic levels. Consistent with high natural levels of P in streams at H.J. Andrews EF, additions of this element produced little biological effect. At Luquillo EF, where rainforest streams are naturally high in both N and P, nutrient bioassays found that increased N and P produced little response in algae, in fungal growth, and in litter decomposition. Grazing pressure by freshwater shrimp in these tropical streams exerted strong top-down control of N and P in food webs. In these stream ecosystems, oxidization of ammonium ions to NO_3^- by microbes provided a significant energy source.

Less extensive studies of nutrient response have been conducted at Marcell and Fraser EFs, Olympic ESF, and Hawai'i ETF. Research at these sites gave indications of nutrient limitation in their streams that were based on the response of single trophic levels, consisting of either primary producers or biofilms, using short-term bioassays, nutrient spiraling studies, or investigations of streams with differing ambient nutrient levels.

Relevance of EFR Nutrient Stressor Research to Regulatory Agencies

The ecosystem-level nutrient addition experiments at Coweeta HL are a model of studies of biological responses to stream nutrients to address needs of the regulatory community for developing nutrient stressor-response models. The approaches taken at Coweeta HL demonstrate the kind of research required to identify biological response thresholds in low-nutrient streams and to disentangle those effects from co-occurring stressors and colimiting factors in these ecosystems. Findings at Coweeta HL that responses to nutrient enrichment varied among trophic levels suggest that methods that only measure biological responses to nutrients in a single basal resource, such as algae or biofilms, may miss important effects on higher trophic levels. Studies at Coweeta HL of both short-term and chronic long-term nutrient additions provide data to address frequency and duration components of nutrient criteria. They also indicate that brief nutrient additions may miss biological responses that are slow to develop. The usefulness to regulators of stream studies at Coweeta HL was recognized by reference to them in the EPA guidance (US EPA 2010) on stressor-response models.

Although nutrient addition experiments at H.J. Andrews, Hubbard Brook, and Luquillo EFs were shorter term than at Coweeta HL, results of these studies give indications of colimiting factors and co-occurring stressors. Studies at these sites investigated responses of food webs and would probably be useful for developing nutrient-stressor-response models in their ecoregions.

Nutrient-stressor-response studies at Fraser and Marcell EFs, Hawai'i ETF, and Olympic ESF demonstrated a variety of approaches that may be useful for studying biological nutrient responses in low-nutrient streams. However, their results were preliminary and may require additional studies to be useful to the regulatory community.

These EFR nutrient-response studies were done in low-nutrient streams that are presumably in the portion of the nutrient gradient in which aquatic biological communities can resist effects of nutrient enrichment. Inferences drawn from stressor-response models may be misleading if they lack data from the resistance portion of the gradient. For that reason, data from EFR studies could be especially useful for regulatory purposes in several parts of the country where studies of nutrient responses in low-nutrient streams are rare or nonexistent.

Studies at EFRs Used for Developing Best Management Practices

Results from management experiments at Coweeta HL; Fernow (chapter 13), Fraser, H.J. Andrews, and Sagehen (chapter 8) EFs; and Caspar Creek Experimental Watersheds (EW) (chapter 11) have been used extensively as a scientific basis for develop-

ing and testing forest best management practices (BMPs). Forest BMPs based on these studies protect water quality by setting operational standards for forestry practices. For example, BMPs often require retaining vegetation in riparian buffers and minimizing runoff and sediment production near streams from road construction, maintenance, and decommissioning; vehicular stream crossings; and slash burning. Although BMPs developed and tested at EFRs have not directly addressed biological responses to stream nutrients, studies at Sagehen EF were used to develop BMPs to address nutrient runoff during fuel reduction treatments; and riparian management BMPs to protect and restore a biological resource, salmonid fish habitat, were developed based on studies at the H.J. Andrews EF (Ryan and Calhoun 2010). Although direct effects of management treatments on stream biological communities have been studied at only three EFRs, (Hubbard Brook EF, Olympic ESF, and Caspar Creek EW), a large body of data on effects of management practices on stream conditions, including nutrients, stream temperature, suspended sediment, and substrate have been collected at several EFRs. Such existing results from EFR management experiments could be drawn upon to develop future BMPs.

Relevance of EFR Findings Not Directly Related to the Focus Question

Our focus groups also identified much additional research done at EFRs of interest to water quality regulatory agencies but not directly related to the focus question. Such research includes effects of natural disturbances on stream conditions, effects of management on streams not directly involving nutrients, and cross-site and regional studies that compare EFR streams with streams affected by different land uses.

Responses to natural disturbances—

Long-term monitoring of stream conditions at all of the reviewed EFRs (see table 19.1) have provided a scientific base for investigating long-term responses of these ecosystems to natural disturbances. For example, monitoring at Luquillo and Santee EFs have documented that stream conditions were strongly changed by storm damage to forests from hurricanes at both these sites and took years to return to predisturbance levels. At Luquillo EF, the detailed mechanisms of the effects of hurricanes were further investigated by experimentally simulating wind damage to vegetation. At Fernow EF, stream macroinvertebrate abundance was drastically decreased after two large floods, but it recovered to predisturbance levels within 4 months after each event. At Hubbard Brook EF, effects on streams of ice storm damage to vegetation have been studied as well as the trajectory of stream conditions as the forest recovered from the disturbance. In mountain basins of the Pacific Northwest, studies at H.J. Andrews EF, Caspar Creek EW, and Olympic ESF have

Table 19.1—Lines of research and monitoring performed at the experimental forests and ranges (EFRs) reviewed in this report that are relevant to water quality regulatory agencies

Omernik Ecoregion																			
(EFR site)																			

Table 19.1—Lines of research and monitoring performed at the experimental forests and ranges (EFRs) reviewed in this report that are relevant to water quality regulatory agencies (continued)

		Omernik Ecoregion (EFR site)													
5.2.1	5.3.1	6.2.3	6.2.7	6.2.10	6.2.12	6.2.12	6.2.12	6.2.14	6.2.14	7.1.8	7.1.8	8.4.3	8.4.4	8.5.3	11.1.1
(MEF)	(HBEF)	(PREF)	(HJA)	(TCEF)	(KREW)	(SHEF)	(FEF)	(GLEES)	(OESF)	(CCEW)	(FER)	(CHL)	(SEF)	(SDEF)	(NA)
Lines of research and monitoring															
Site conditions studied or monitored:															
Climate data, long term (>5 yr)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Precipitation chemistry	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Riparian large wood	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓			
Riparian vegetation	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Reference watershed/stream monitored	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Site land use history documented	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Site upland vegetation data	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Other relevant studies and monitoring:															
Management experiments	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
Cross-site or regional monitoring/experiments	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

MEF = Marcell Experimental Forest (EF), HBEF = Hubbard Brook EF, PREF = Priest River EF, HJA = H.J. Andrews EF, TCEF = Tenderfoot Creek EF, KREW = Kings River Experimental Watersheds/Teakettle EF, SHEF = Sagehen EF, FEF= Fraser EF, GLEES = Glacier Lakes Ecosystem Experiments Site, OESF = Olympic Experimental State Forest, CCEW = Casper Creek Experimental Watersheds, FER = Fernow EF, CHL = Coweeta Hydrologic Laboratory, SEF= Santee EF, SDEF = San Dimas EF, LEF = Luquillo EF, HETF = Hawai'i Experimental Tropical Forest. Methods used and depth of study on these topics are not uniform across sites.

found that debris flows are natural disturbances that significantly alter physical and chemical conditions in streams of that region. Debris flows change stream geomorphology by adding large wood and rocks to channels, and create riparian conditions that favor establishment of alder, a successional, N-fixing tree that can increase dissolved N in stream water. In fire-prone western states, scientists at EFRs have studied effects on streams of severe wildland fires. Results from Sagehen and San Dimas EFs, for example, have contributed to the understanding of the effects on water quality of severe wildland fires and postfire revegetation.

Natural disturbances affect not only stream nutrients but also stream physical conditions, such as flow, temperature, and suspended sediments. They contribute to the variability in stream conditions that are often a source of uncertainty for regulatory purposes, including setting water quality criteria. Long-term data on stream conditions from these EFRs could be useful for developing models of ecosystem response to natural disturbances to reduce this source of uncertainty in regulatory decisionmaking.

Forest management experiments—

Landscape-scale ecosystem manipulations, particularly forest management experiments, have been implemented at many EFRs (table 19.1). The charters of most of the reviewed EFRs enable scientists to perform experiments at these sites that disturb soils and vegetation, including forest management practices. Exceptions are Luquillo EF, Glacier Lakes Ecosystem Experiments Site (GLEES) (chapter 10), and Hawai'i ETF, which have land use designations that do not allow such manipulations. Studies of environmental effects of forest management practices at EFRs typically use multidisciplinary approaches and investigate complex landscape-scale interactions that produce long-term effects on ecosystem properties, including water quality. For example, at Fraser EF in the Rocky Mountains, studies found that timber harvest increased both peak flows and sediment loads in streams. Hydrologic analyses showed that a postharvest increase in the duration of bank-full flows, which are most effective for channel scour and sediment transport, could account for the increased stream sediment loads. At Fernow EF in the Appalachians, forest roads used in timber operations, especially near streams, were identified as the largest source of increased stream sediments. At Caspar Creek EW in the California Coast Ranges, monitoring showed stream sediment loads increased 30 years after cutting, and analyses found that deterioration of legacy forest roads and skid trails, originally installed to remove timber, caused the delayed response. As these examples illustrate, long-term and detailed studies at EFRs have revealed that forest management practices produced impacts on water quality via complex interactions,

and that these effects can differ among ecoregions and management practices. Similar examples could be cited for effects of management in other ecoregions and on other stream parameters, including water temperature, light, and the amount of in-channel large wood.

Cross-site and regional studies—

Studies at cross-site and regional scales that have been conducted at many of the EFRs may be useful to regulatory agencies for addressing multiregional and national issues, such as effects of land use and changing climate. The Lotic Intersite Nitrogen Experiment is an outstanding example of a cross-site study that investigated mechanisms of instream N processing using stream additions of isotope-labelled ^{15}N . This treatment was repeated at multiple sites in several ecoregions, including the Coweeta HL, and the Hubbard Brook, H.J Andrews, and Luquillo EFs. Results revealed detailed mechanisms of the fate and transport of N in relatively undisturbed streams and how they compared in different ecoregions. Important biological processes involving N in streams were measured, such as nitrification, uptake of N from stream water, denitrification, and incorporation of N into stream trophic webs and riparian vegetation. Such basic understanding of ecological processing of stream N could be useful to regulatory agencies for many purposes including, for example, developing more realistic total maximum daily load (TMDL) models.

Regional-scale studies, performed at Coweeta HL and Hubbard Brook, H.J. Andrews, and Luquillo EFs compared stream conditions in relatively undisturbed EFR streams, with streams affected by other, more intensive land uses. Results showed that urban and agricultural development in these ecoregions generally elevated stream nutrients above baseline levels found in forest headwaters on these EFRs.

EFRs have also participated in numerous nationwide environmental monitoring networks, such as the National Atmospheric Deposition Program Network, which synthesizes atmospheric deposition data collected at sites across the country into national maps. Other multisite data syntheses, such as the analysis of hydrological responses to changing climate by Jones et al. (2012), have drawn upon EFR long-term monitoring data. Atmospheric deposition and streamflow are important contributors to water quality, and multiregional analyses of these factors could be useful to regulatory agencies for anticipating patterns and trends in water quality at multiregional or national scales. Ryan and Swanson (2014) and Stine (2016) describe participation of EFRs in cross-site research and monitoring networks more fully.

Priority Regulatory Research Needs That Might Be Filled by Future Studies at EFRs

This report identifies the highest priority research needs of water quality regulatory agencies that potentially could be filled by future research at the individual EFRs (table 19.2). These are scientific questions of importance to regulatory agencies that cannot be fully answered with existing science. They fall into several categories reflecting differences in the ecoregions and research histories of these EFRs. They include questions about the composition of stream biological communities, especially in low-nutrient reference streams, and their biological responses to nutrient enrichment; effects on streams from atmospheric deposition of air pollutants, especially the nutrients N and sulfur; effects of forest management practices on methylmercury accumulation in stream food webs and on stream dissolved organic carbon and carbon cycling; and effects on stream biological communities of changing climate, especially increasing drought.

Biological Communities in Reference Streams

To fill the identified needs of the water quality regulatory agencies for better characterizations of biological communities in reference streams, repeated and more comprehensive biological surveys of EFR streams were proposed. Results of such studies might be useful to regulators for developing biological indicators for water quality criteria using the reference waterbody approach. To meet the data requirements of regulatory agencies, it would be best if such surveys were conducted using protocols developed by those agencies.

Thresholds of nutrient response—

Threshold levels of nutrient enrichment that elicit biological responses in reference streams were cited as priority regulatory research needs at several EFRs. Filling these needs would be potentially useful to regulatory agencies for setting water quality standards that protect biological communities in relatively undisturbed streams with low-nutrient condition. Outside of EFRs, studies of biological thresholds to nutrient enrichment have typically been done in streams with nutrient loads higher than are usual in forest streams. Future research to fill these needs would include bioassays and nutrient additions to low-nutrient streams at EFRs to study biological responses in multiple trophic levels and to short-term and chronic nutrient additions. EFRs would be well suited as sites for such future investigations because EFR watersheds have the rare combination of both access for study and control of future onsite human activities that affect nutrient status.

Table 19.2—Highest priority research needs of water quality regulatory agencies that might be filled by future research at experimental forests and ranges (EFRs) reviewed in this report

Ecoregion	Experimental forest/range	Highest priority regulatory science need related to N and P	Highest priority regulatory science need related to N other nutrients
5.2.1	Marcell EF, Minnesota	Ambient nutrients effects on peatland aquatic biology	Factors affecting sulfate and methylmercury in wetlands
5.3.1	Hubbard Brook EF, New Hampshire	Effects of changing ambient stream chemistry on stream biology	Biological response to base cation depletion
6.2.10	Tenderfoot Creek EF, Montana	Effects of instream processes on stream water nutrients	Baseline indicators of functioning stream ecosystems
6.2.12	Sagehen EF, California	Effects of slash burning on stream nitrate levels	Effects of forest management on chemistry and biology of springs
6.2.12	KREW/Teakettle EF, California	Effects of fuels management on stream N, P, and biological indicators	Effects of forest fuels management on carbon cycling
6.2.14	GLEES, Wyoming	N deposition rate that would exceed biological response thresholds	Acidic deposition effects on aquatic chemistry and biology
6.2.14	Fraser EF, Colorado	Composition of biological communities in reference streams	None identified
6.2.3	Priest River EF, Idaho	Effects of timber harvest on streambank stability and water quality	None identified
6.2.7	H.J. Andrews EF, Oregon	Effects of nutrients on biological communities in reference streams	None identified
7.1.8	Caspar Creek EF, California	Riparian effects on instream nutrient dynamics	Effects of logging on stream carbon storage and exports
7.1.8	Olympic ESF, Washington	Effects of forest management on stream habitat for salmonids	Forest management and sulfate effects on methylmercury in food webs
8.4.3	Fernow EF, West Virginia	Effects of N deposition on stream nitrate export	Base cation depletion by logging and atmospheric deposition
8.4.4	Coweeta HL, North Carolina	Biological response thresholds to long-term nutrient loading	Effects of land use change on stream DOM
8.5.3	Santee EF, South Carolina	Biotic indicators of reference conditions and responses to nutrients	Effects of fire and sulfate loading on methylmercury in food webs
11.1.1	San Dimas EF, California	Effects of N deposition on stream nitrate export	None identified
N/A	Luquillo EF, Puerto Rico	Effects of drought and reduced flow on biotic responses to N and P	Effects of instream processes on DOC
N/A	Hawai'i ETF, Hawai'i	Biological communities and nutrient responses in reference stream	Sources and fates of stream DOC and inorganic carbon

N = nitrogen, P = phosphorus, N/A = not applicable, EF = Experimental Forest, ESF = Experimental State Forest, HL = Hydrologic Laboratory, ETF = Experimental Tropical Forest, DOM = dissolved organic matter, DOC = dissolved organic carbon, GLEES = Glacier Lakes Ecosystem Experiments Sites, KREW = Kings River Experimental Watersheds.

Needs With Regional Implications for Water Quality

Filling the research needs identified at some individual EFRs might help regulatory agencies address important regional water quality issues. For example, high stream nitrate levels have been observed in reference streams at both San Dimas EF in southern California and at Fernow EF in West Virginia. At San Dimas, average NO_3^- concentrations in reference streams are ~70 percent of the drinking water standard, and streams can exceed that standard following prescribed fire treatments. At Fernow, average stream water NO_3^- concentrations are 8.4 percent of the drinking water standard but have increased threefold since 1980 and are much higher than other forest study streams in the eastern United States (Argerich et al. 2013). Although geographically separated, stream chemistry at both these sites has been influenced by long histories of high atmospheric deposition of N from air pollution. If these EFR streams are representative of forest headwaters in their respective ecoregions, they may indicate that there is significant loading of NO_3^- to streams draining upland forests in response to high deposition of N over past decades. In southern California, such a finding might implicate upland streams as an important source of NO_3^- pollution to regional groundwater that supplies drinking water. In the mid-Atlantic states, such a finding might be evidence that streams from upland forests are a significant source of NO_3^- flowing via rivers to Chesapeake Bay. Both of these regions have already invested heavily to control nutrients from urban and agricultural sources, so any greater reductions of those sources, to compensate for rising NO_3^- from forests, might be costly. Future research at these two EFR sites, and especially investigations of how applicable their results are to forests across their respective regions, can help water quality regulatory agencies better understand the implications for water quality of long-term atmospheric deposition of N to forests in these regions.

Research at other EFR sites also indicates that ecosystems are not equally vulnerable to alteration by atmospheric deposition of N. For example, unlike EFRs in West Virginia and southern California, studies at Kings River EW/Teakettle EF (chapter 7), in California's Sierra Nevada Mountains, found that relatively high levels of N deposition were not reflected in stream nutrient concentrations at this site. N cycling and retention processes in soils and vegetation within this ecosystem are apparently adequate to buffer streams from atmospheric inputs of N.

In several ecoregions, regulators identified a priority need for research on the accumulation of mercury (Hg) in aquatic food webs of wetland or alpine streams, and how deposition of air pollutants and forest management practices may affect that phenomenon. This need was cited at Marcell EF, in the Lake States, and Santee EF (chapter 15), in the southern coastal plain, both in ecoregions with substantial wetland areas, and at GLEES and Olympic ESF, in mountainous areas of western

states. Future research to fill this need might include studying effects of forest land management, and atmospheric deposition of sulfate (SO_4^{2-}) on Hg accumulation in stream food webs. Results of future research at EFRs might be useful to regulatory agencies by providing a scientific basis for developing rules to reduce the environmental hazard of Hg to human health.

Needs Related to Forest Management

Effects of forest land management practices on water quality were identified as a research need of regulatory agencies that might be filled by future research at EFRs in several parts of the country. Such science might be useful to regulatory agencies for developing science-based rules and guidelines for forest management practices to protect water quality. The specific practices of concern varied among regions. For example, effects of forest fuels reduction treatments were cited in fire-prone southern and western forests, whereas effects of harvesting timber were issues in regions with less fire risk. A question of interest, particularly in western states, is how much riparian zone protection is needed in harvested areas to ensure that conditions in forest streams, including nutrient levels, will sustain healthy aquatic biological communities. Also of interest to regulators were effects of forest management on carbon sequestration and greenhouse gas emissions from both upland and stream ecosystems. Regulators could use research on this topic for developing regulations that consider effects of management on stream DOM, which may degrade water quality for drinking water and for aquatic habitat, and guidance of forest practices to reduce potential effects on climate.

Long-term environmental monitoring at EFRs, especially of streams, might contribute to efforts by the water quality regulatory community to measure effects of changing climate. For example, the EPA is establishing regional monitoring networks across most EPA regions that collect data on aquatic biota, flow, and temperatures to be used for recalibrating standards and criteria as baseline conditions shift. Regulatory agencies could draw upon long-term monitoring and results of research at EFRs to supplement their monitoring effort and to interpret its results.

If regulatory agencies wish to sponsor future research at EFRs, they would benefit by developing cooperative relationships with the research site managers at the individual EFRs where studies would be located. Before on-the-ground research can be undertaken at an EFR, it must first be approved by the local site manager, regardless of who is performing the work and which agency funds the study. The local site managers coordinate research activities at their EFR to avoid conflicts among multiple research projects and to maintain the integrity of their site for future studies.

Discussion

Important Traits of Headwater Streams

Studies at EFRs provide evidence that forested headwater streams have characteristics that may have important implications for water quality and stream biological communities at the national scale. However, these traits have not been investigated widely across ecoregions. Specifically, headwater streams usually have reaches with flow regimes that are ephemeral or intermittent and food webs that are based on detritus. Both conditions may influence water quality and aquatic biological communities in headwaters, but these characteristics have been studied in detail in relatively few ecoregions. How widely these findings apply to streams in other ecoregions has not been thoroughly investigated.

Ephemeral and Intermittent Streams

EFR study watersheds contain low-order stream reaches with ephemeral or intermittent flows. Ephemeral reaches have surface flows only following wet periods, such as rain events or snowmelt. Intermittent reaches flow most of the time, but cease flowing during extended dry periods. Water quality in ephemeral and intermittent reaches are topics of regulatory interest in many parts of the country because such low-order streams comprise a substantial portion of the channel length in many drainage basins. Most aquatic research, however, has been done on perennial streams and, as a result, there is considerably less science to support regulatory decisions about ephemeral and intermittent streams. Studies in some EFRs have found that intermittent or ephemeral streams may have nutrient characteristics different from those found in perennial streams. For example, investigations at Hawai'i ETF found ephemeral streams showed signs of nutrient limitation that may differ from those in perennial reaches. EFRs could serve as research platforms in a variety of ecoregions to investigate important questions about the aquatic communities and water quality that occur in ephemeral and intermittent reaches. This research could investigate questions such as (1) how biological responses to nutrients in ephemeral and intermittent streams compare with downstream, perennial reaches and how that relationship varies across ecoregions; and (2) what level of riparian protection measures would support appropriate nutrient input to these small headwater streams?

Detrital-Based Food Webs in Headwater Streams

Studies at Coweeta HL and Hubbard Brook and Luquillo EFs found that at those sites, headwater streams under closed-canopy forests have low ambient light conditions and energy flows in food webs that are primarily based on allochthonous

inputs of detritus such as leaf litter from streamside vegetation. In contrast, food webs in larger, sunlit streams are usually based on in-channel photosynthesis by aquatic autotrophs such as algae and periphyton (Vannote et al. 1980). The strong effects of riparian vegetation on energy flow and nutrient dynamics in detrital-based streams produces food webs and biological responses to nutrients that differ from those in autotrophic-based streams (Richardson and Danehy 2007). Forest headwater streams in many parts of the country, including most streams studied on EFRs, have closed canopies and low light during the growing season, and often are detrital based. However, the majority of stream research outside of EFRs, has been done in larger, sunlit streams that are autotroph based. As a result, science available to water quality regulatory agencies is predominantly derived from studies of autotroph-based streams rather than detrital-based streams, and current EPA guidance for nutrient criteria does not address detrital streams. A large national study, sponsored by the National Science Foundation and its partners, called STREAM Experimental Observatory Network (STREON) (McDowell 2015), is planning to investigate long-term biological responses to nutrient enrichment in selected streams nationwide. However, only a few STREON experiments in a small number of ecoregions will examine detrital-based streams.

If regulatory agencies need scientific evidence of ecosystem responses to nutrients in detrital streams on a wider array of ecoregions, the results of stream enrichment studies at EFRs are an existing body of knowledge on that topic. Future research in EFR streams could offer opportunities to broaden the understanding of detrital stream processes to additional ecoregions by investigating questions such as, what are biological responses to nutrient enrichment in detrital-based, headwater streams, and how do they compare across a range of ecoregions?

Potential Uses of EFRs as Research Networks

From a national perspective, multiple EFRs could potentially be used as study networks to address research needs of the water quality regulatory community at scales larger than individual EFRs or ecoregions. A number of findings at individual EFRs have important implications for water quality and stream biological communities. However, how broadly these findings can be applied across multiple ecoregions has not been systematically investigated. Studies to test whether EFR science findings of interest to regulatory agencies can be extended to additional ecoregions could take several forms. For example, synthetic analyses could draw upon existing data or research findings from multiple EFRs to compare ecosystem responses to stressors in different ecoregions, or

cross-site field experiments could be performed in several EFRs to investigate such responses across ecoregions. EFRs with stream studies offer a wide menu of sites for investigations that compare ecoregions because they are located in 14 states and the Commonwealth of Puerto Rico, and represent 12 Omernik ecoregions plus two tropical forests without Omernik ecoregional classifications (Omernik and Griffith 2014) (fig. 1.1 and table 1.1). Studies using EFRs as a network might address larger scale questions such as these: How has stream NO_3^- in reference streams responded to the history of atmospheric deposition rates in ecoregions across the country? Do threshold levels of nutrient enrichment that produce biological responses in low-nutrient, forest streams vary across multiple ecoregions? How does Hg accumulation in stream food chains respond to influences such as atmospheric deposition of SO_4^{2-} and forest management across a range of ecoregions?

Dual Capability of EFRs for Addressing Regulatory Science Needs

EFRs potentially offer water quality regulatory agencies a dual capability for addressing science needs. The substantial body of existing published research and environmental databases developed at EFRs provides a body of science that is available to be mined for regulatory purposes. EFRs could also serve as venues for future research to fill important regulatory science needs.

The dual potential of EFRs could be helpful to regulatory agencies for resolving emerging issues. For example, EFRs could be used to address the unresolved question of how to incorporate into water quality criteria the phenomenon that baseline stream conditions in reference streams in some parts of the country have been changing over periods of decades. Results of long-term monitoring and intensive studies of EFR reference streams could be drawn upon to develop models of stream ecosystem responses to changing climate and air pollution deposition. In the near term, such models might be used to create forecasts of changes in reference stream conditions for adapting water quality criteria to future scenarios of climate and atmospheric deposition. These ecosystem models might also serve to identify key areas of scientific uncertainty in those forecasts and to design future research on streams in EFRs to narrow those uncertainties. Thus the complementary capabilities of EFRs as repositories of existing research results and long-term environmental data and as platforms for future, gap-filling studies might be combined by the regulatory community to address emerging scientific needs.

Other Potential Uses of This Synthesis

Uses by the Research Community

This synthesis may be useful to research scientists for identifying how the work they do at EFRs is relevant to issues of concern for water quality regulatory agencies. It may also help them find areas of common interest for potential future collaborative research with regulatory agencies. Research of practical interest to regulatory agencies might also address some basic ecological questions. For example, research on biological responses to nutrients in detrital streams might shed light on how the structure and function of detrital streams affect the resistance and resilience of these ecosystems to stress or disturbance.

Uses by the Forest Industry

This synthesis summarizes a great deal of science that may be useful for both forestry practitioners and research scientists in the forest industry. Forest industry and water quality regulatory agencies have a common interest in maintaining clean water from forest lands, although industry and government may use science for different purposes.

EFRs are relevant to the forest industry for several reasons. EFR forests are located within the major “timber basket” ecoregions that contain the most important commercial forests. In addition, many EFRs have hosted some of the original and long-running scientific studies of the environmental effects of forest management practices, particularly on streams. Consequently, research results from several EFRs have been used to formulate BMPs to protect water quality during forest management operations. EFRs also have a wide variety of environmental monitoring that provides a long-term context useful for indepth interpretation of the results of these management experiments. Furthermore, the large body of already existing research results and long-term environmental datasets that have been built at EFRs are in the public domain and freely accessible to industry. These EFR research products are a rich body of science that can be relied upon by research scientists in the forest industry.

Biological responses to stream nutrients, the main theme of this report, have been studied at several EFRs mostly in the eastern and southern states, with relatively little of this work conducted in other parts of the country, most notably in the West. Given that nutrients in forest streams in the West have historically been very low and generally not a regional concern for water quality, the lack of such studies there is neither surprising nor much of a shortcoming from an industry perspective. Two EFs, San Dimas EF in California and Fernow EF in West Virginia, are excep-

tions. They have high N levels even in undisturbed forest streams, likely the result of a long history of high atmospheric deposition of N from air pollution in both regions. Science from these forests with high stream nitrate levels may be useful for understanding nutrient responses in streams of industrial forests in regions undergoing high air pollution stress.

Long-term studies of reference watersheds that receive minimal on-site human disturbance at most EFRs have great potential to be useful to the forest industry. They provide important documentation of the range, frequency, and duration of natural variability in background water quality in streams in unmanaged landscapes. Their wide geographic distribution provides evidence that baseline conditions in forest streams differ region to region depending on variables such as climate, underlying geology, and forest vegetation types. These long-term studies have also found that, in some parts of the country, background water quality has significantly changed over decades. Forest land managers may need to consider in their long-range planning the scientific evidence that baseline stream conditions may be dynamic in some regions. Causes of these trends on reference watersheds are being investigated at EFRs. Outcomes of these studies may be useful to the forest industry to anticipate what effects large-scale stressors, such as changing climate or air pollution, may have on industrial forests.

Overall, for planning and improving their operations, land managers and research scientists working in the forest industry could benefit from drawing upon the body of science from the EFR sites in their ecoregion, and neighboring ecoregions. In addition, in interactions with water quality regulatory agencies, industry representatives may find that science from EFRs is useful for developing science-based regulations.

Uses by Research Leaders of Land Management Agencies

For science leaders and administrators in the U.S. Forest Service (USFS) and state agencies that manage EFRs, this report suggests opportunities to cooperate with state and federal water quality regulatory agencies to develop mutually beneficial research. The number of potential partners is large because each state has one or more agencies with water quality regulatory responsibilities, and the federal EPA has several regional offices. Administrators of EFRs might work together with regulatory agencies to encourage and possibly co-fund research to address the kinds of science needs identified in this report. For example, by working together, the USFS and regulatory agencies might extend aquatic biological monitoring done by regulatory agencies to streams in EFRs. This kind of cross-agency cooperation would require effort, but if done well, might produce useful science for both environmental regulators and land managers.

This synthesis suggests that, to encourage closer ties with water quality regulatory agencies, the USFS and state agencies that manage EFRs could make EFR data of interest to regulators more widely accessible. A current example of easy access to EFR data is ClimDB/HydroDB (LTER Network 2013), which provides online EFR long-term daily weather and streamflow datasets. Many more opportunities exist to enhance the usefulness of EFR datasets. For example, StreamChemDB (Oregon State University 2011), a website that shares water chemistry monitoring data from some EFR streams, might be expanded by adding more EFRs and cooperating study sites managed by other organizations. Water quality data from some EFRs are available online via the Water Quality Portal (National Water Quality Monitoring Program, n.d.), which is jointly operated by the U.S. Geological Survey and the EPA. Data from additional EFRs could be shared via this portal. Online applications could also be developed to give access to additional classes of EFR data of interest to regulators, such as surveys of aquatic biology, stream geomorphology, substrate, large wood, and riparian vegetation of EFR streams. Expediting release of data from EFR monitoring and studies would enhance their use, even if it requires labelling data as “provisional” while quality control is pending.

An administrative change by the USFS could potentially strengthen future research at three EFRs reviewed in this report. Unlike the other EFRs with stream research, Priest River (chapter 4), Sagehen, and Tenderfoot Creek (chapter 6) EFs currently do not have officially designated reference subwatersheds. The future value of stream research at these EFRs could be enhanced if the USFS revised their charters to formally designate one or more reference subwatersheds at each site to be managed for minimal onsite human disturbance.

Conclusions

EFRs are a network of intensively studied ecosystems that are important sources of scientific information on streams and watersheds in forested ecoregions across the country. The publically available body of published research and long-term environmental data from these dedicated study sites can be used by water quality regulatory agencies for a variety of practical purposes. Datasets relevant to the focus question, “What are the biological responses to stream nutrients?” have been collected at all the EFRs reviewed, and one aspect of this question, dose response, has been investigated indepth at eight EFRs, with the most extensive studies at Coweeta HL. Results of ecological research at EFRs into the mechanisms that underlie ecosystem responses to nutrients has a high potential for use by regulatory agencies to develop scientifically based models of stream processes.

Pressing research needs of the regulatory community could be filled by future research at EFRs. Such needs include an understanding of the composition of biotic communities and their responses to nutrient enrichment in low-nutrient reference streams, and effects on streams of forest management practices, atmospheric deposition, and changing climate. Filling these needs could potentially help the regulatory community address water quality issues in several parts of the country. Used as research networks, EFRs offer opportunities to increase the scientific understanding of ecological processes in headwater reaches, a major class of streams that are underrepresented in the scientific literature. The implications for water quality of ecological conditions in these low-order streams, such as detritus-based food webs and ephemeral and intermittent flow regimes, are not well understood. Cooperative research efforts between water quality regulatory agencies and land management agencies that maintain EFRs have strong potential to produce mutual benefits. Land management and environmental regulatory agencies could potentially derive mutual benefits from cooperation on research about other topics beyond water quality, for example, studies of air pollution from wildland fires. This report might provide a template for initiating joint efforts by these agencies to advance such research.

Next Steps

This synthesis is an initial step toward making science from EFRs more available to the water quality regulatory community. Following are some additional actions that might further that goal:

1. Assemble a joint task group consisting of EFR scientists and administrators from USFS Research and Development, cooperating agencies and institutions, and representatives of state and federal water quality regulatory agencies. This group would identify existing datasets and research products from EFRs that are of highest potential for use by regulatory agencies and propose actions that would promote that use.
2. Have an appropriate cross-agency task force evaluate what future research at EFRs would be mutually beneficial to regulatory agencies and land management agencies and develop joint proposals for research to address the most promising questions.
3. Organize an EFR science user group of water quality regulatory agencies to inform each member about their uses of research results from EFRs. This group would also provide the USFS with feedback about how EFR science might be made more useful for regulators on a continuing basis.
4. Make scientific data collected at EFRs more readily available to water quality regulatory agencies and the public.

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