Chapter 19: An Overview and a National Perspective

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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 developing 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)																
	5.2.1	5.3.1	6.2.3	6.2.7	6.2.10	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	NA	NA
Lines of research and monitoring	(MEF)	(HBEF)	(PREF)	(HJA)	(TCEF)	(KREW)	(SHEF)	(FEF)	(GLEES)	(OESF)	(CCEW)	(FER)	(CHL)	(SEF)	(SDEF)	(LEF)	(HETF)
Stream nutrient monitoring:																	
Stream nutrient concentration, long term (>3 yr)	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Stream biology studied or monitored:																	
Aquatic species composition:																	
Invertebrates	✓	✓	✓	✓		✓			✓	✓	✓	✓	✓	✓		✓	✓
Vertebrates	✓	✓		✓						✓	✓	✓	✓	✓			✓
Algae		✓		✓		✓			✓	✓	✓		✓			✓	✓
Macrophytes		✓											✓				
Aquatic biological functions:																	
Stream photosynthesis/ chlorophyll *a*	✓	✓		✓	✓	✓			✓	✓	✓		✓			✓	✓
Stream respiration		✓		✓	✓						✓		✓			✓	✓
Food web interactions		✓		✓			✓			✓	✓		✓				✓
Chemical indicators of biological activity	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
Factors influencing biological responses:																	
Streamflow, long term (>5 yr)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Light and shade on stream	✓	✓		✓	✓	✓				✓	✓	✓	✓			✓	✓
Stream temperature data	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Turbidity/suspended sediments				✓	✓	✓	✓	✓		✓	✓	✓	✓			✓	✓
Dissolved organic matter	✓	✓		✓	✓		✓	✓		✓	✓	✓	✓	✓		✓	✓
Particulate organic matter		✓		✓			✓	✓			✓	✓	✓			✓	✓

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	6.2.14	6.2.14	7.1.8	7.1.8	8.4.3	8.4.4	8.5.3	11.1.1	NA	NA
Lines of research and monitoring	**(MEF)**	**(HBEF)**	**(PREF)**	**(HJA)**	**(TCEF)**	**(KREW)**	**(SHEF)**	**(FEF)**	**(GLEES)**	**(OESF)**	**(CCEW)**	**(FER)**	**(CHL)**	**(SEF)**	**(SDEF)**	**(LEF)**	**(HETF)**
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 accross 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 regualtory science need related to N and P	Highest priority regualtory science need related to 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 exceptions. 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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