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

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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

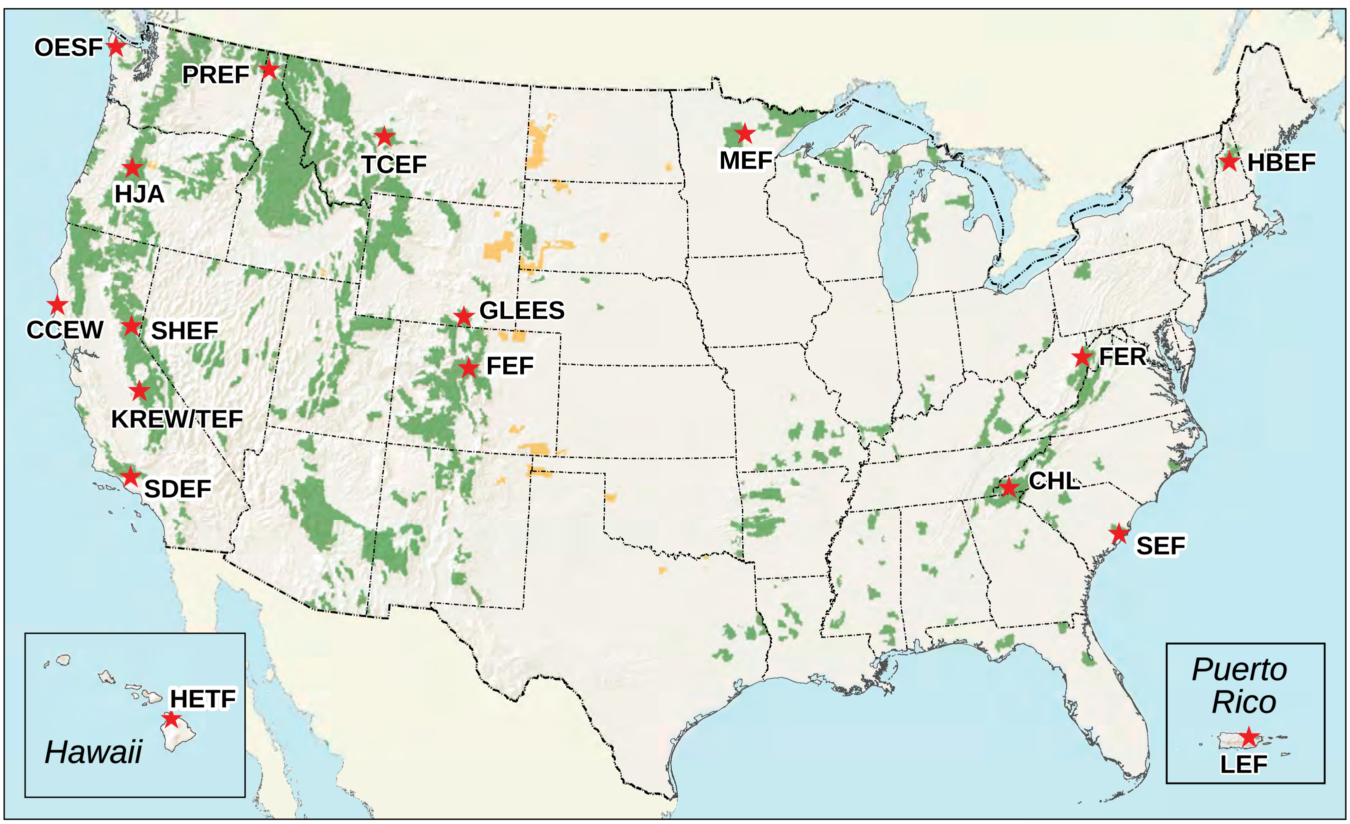

Figure 1.1—Experimental forest and range (EFR) sites with intensive stream studies that are reviewed in this synthesis. Key to EFR sites: MEF = Marcell Experimental Forest (EF), HBEF = Hubbard Brook EF, PREF = Priest River EF, HJA = H.J. Andrews EF, TCEF = Tenderfoot EF, KREW/TEF = Kings River Experimental 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 Omernik Ecoregions (level III) and Bailey Ecosystem Provinces

EFR site	State	Omernik 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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