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

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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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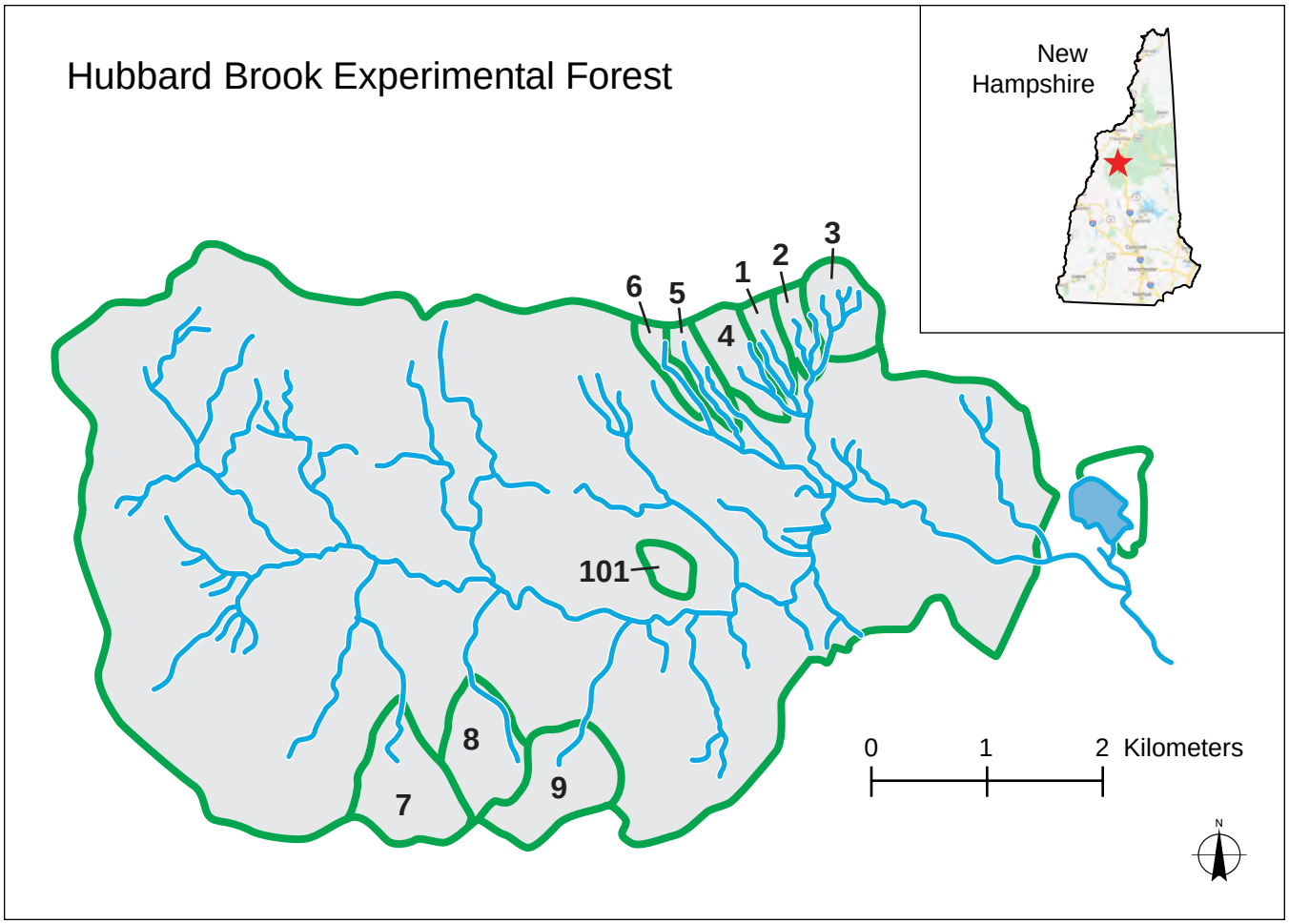

Figure 3.1—Hubbard Brook Experimental Forest. Numbers identify study watersheds.

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 μg N/L to >5 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

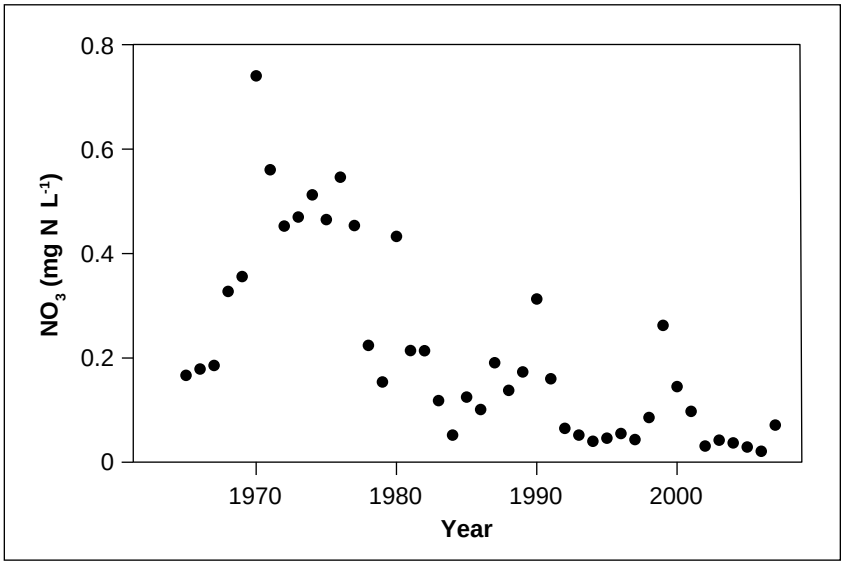

Figure 3.2—Time series of annual volume-weighted nitrate (NO_3^-) -N concentrations in stream water from a watershed at Hubbard Brook Experimental Forest shows strong variation through time with decline following 1980. Data source is from Likens (2012).

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 µg N/L (Bernhardt et al. 2002, Hall et al. 2002).

Stream water P concentrations are very low. Dissolved P is <10 µg P/L. Particulate P is <1 µg P/L at baseflow, but can increase to 100 µg 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*

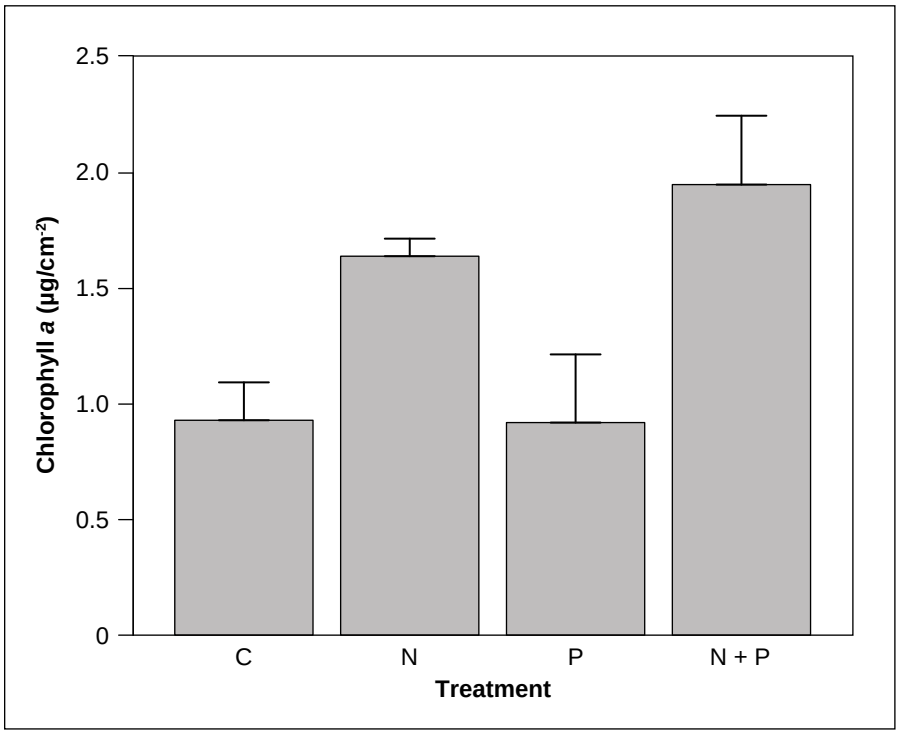

Figure 3.3—Response of bioassay experiment in Bear Brook shows strong response to nitrogen (N) alone in 1997. C = carbon, P = phosphorus. Data from Tank and Dodds (2003).

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 Responces 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 $^{15}NH_4^+$ to streams across the United States. Relative to other sites during the 1997 additions, Bear Brook had high rates of regeneration of labeled $^{15}NH_4^+$, 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 eplilithic 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.

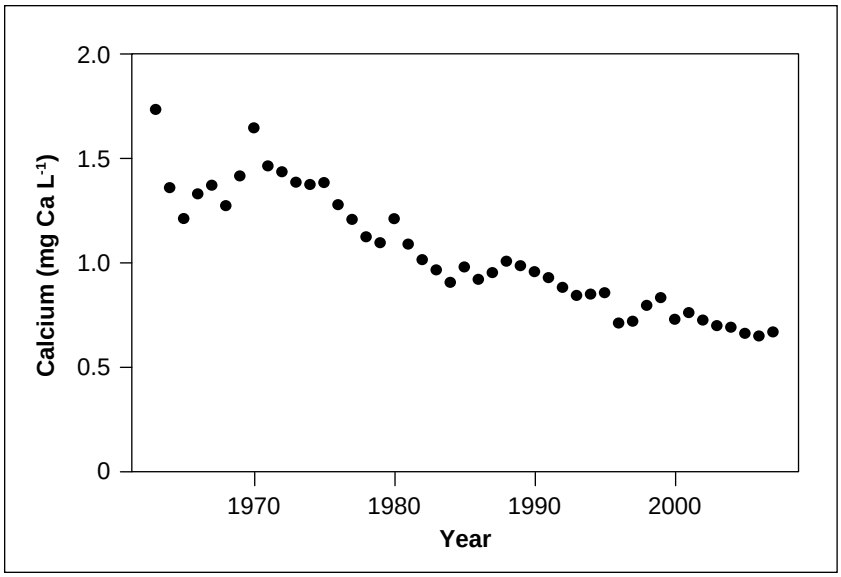

Figure 3.4—Time series of annual volume-weighted dissolved calcium (Ca) concentrations in stream water from a watershed at Hubbard Brook Experimental Forest shows strong decline through time as Ca is leached from forest soils. Data are from Likens (2012).

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 (*Rhinichthyes 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.

Acknowledgments

Emily Bernhardt, John Campbell, Winsor Lowe, Doug Ryan, and Bob Stelzer provided useful comments on an earlier draft of this manuscript.

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