

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

Sherri Johnson, Alba Argerich, Aron Borok, Daniel Sobota, and Robert J. Danehy¹

Introduction

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

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

Site Description

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

¹ **Sherri Johnson** is a supervisory research ecologist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR 97331; **Alba Argerich** is an assistant professor in aquatic ecology, University of Missouri, School of Natural Resources, Columbia, MO 65211; **Aron Borok** is a water quality standards specialist and **Daniel Sobota** is a water quality analyst, Water Quality Program, Oregon Department of Environmental Quality, 700 NE Multnomah Avenue, Portland, OR 97232; **Robert J. Danehy** is an aquatic biologist, Catchment Aquatic Ecology, 5335 Saratoga Street, Eugene, OR 97405.

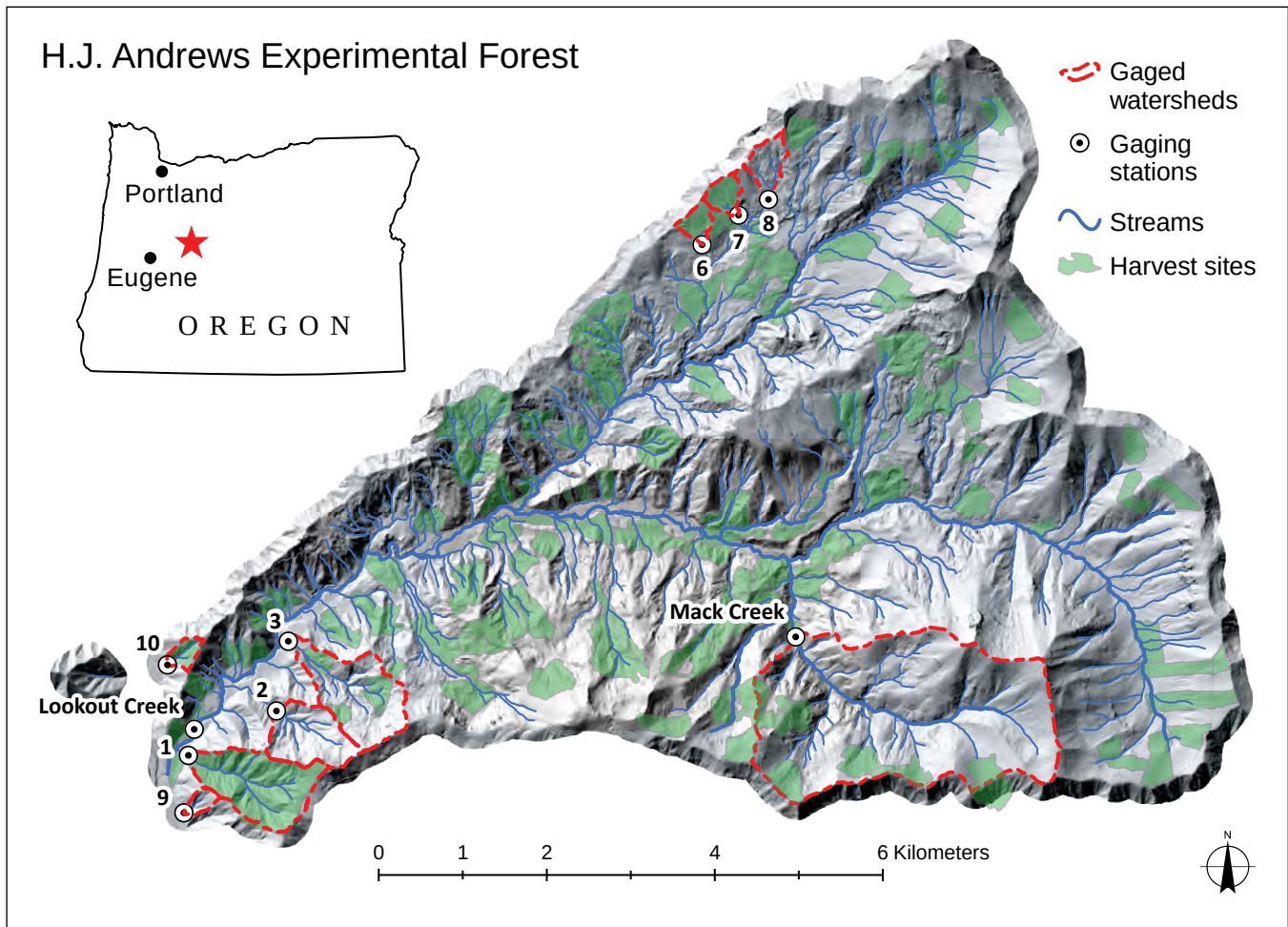


Figure 5.1—H.J. Andrews Experimental Forest and its small study watersheds that have been monitored for decades.

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

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

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

Research History

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

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

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

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

— = not available.

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

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

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

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

Availability of Publications and Data

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

Biological Responses to Stream Nutrients N and P

Issues of Concern

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

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

Findings From Studies

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

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

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

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

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

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

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

Short-term studies of nutrient concentrations and export dynamics—

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

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

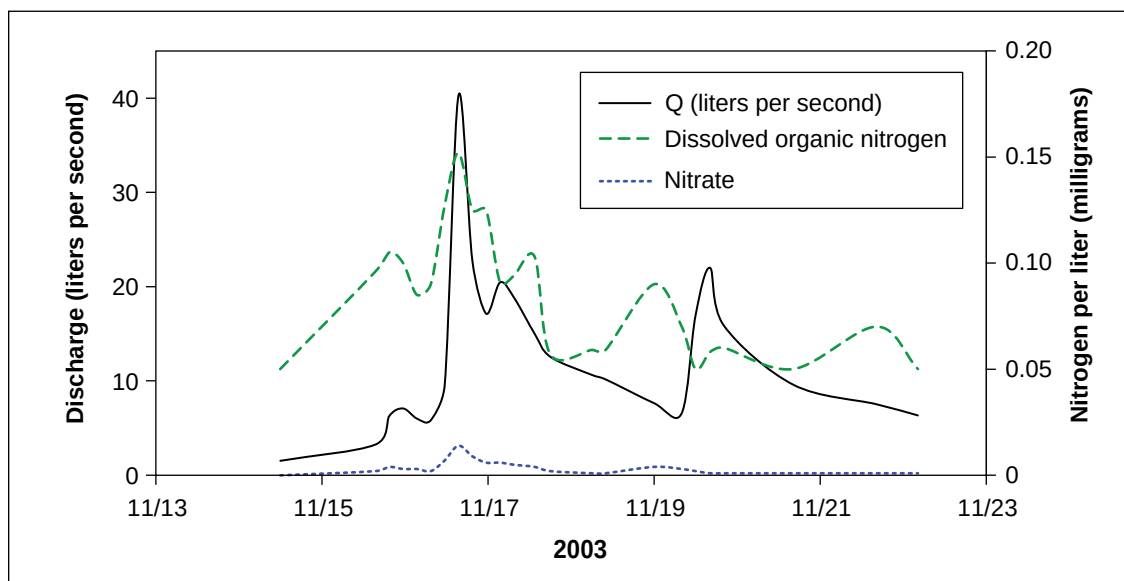


Figure 5.2—Concentrations of dissolved organic nitrogen and nitrate (NO_3^-) in watershed 2 during stormflow in November 2003 (Hood et al. 2004, Johnson 2007).

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

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

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

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

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

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

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

— = not reported

FBOM = fine benthic organic matter.

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

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

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

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

Dose-Response Studies

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

Reference Watersheds

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

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

Responses to Management and Natural Disturbances

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

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

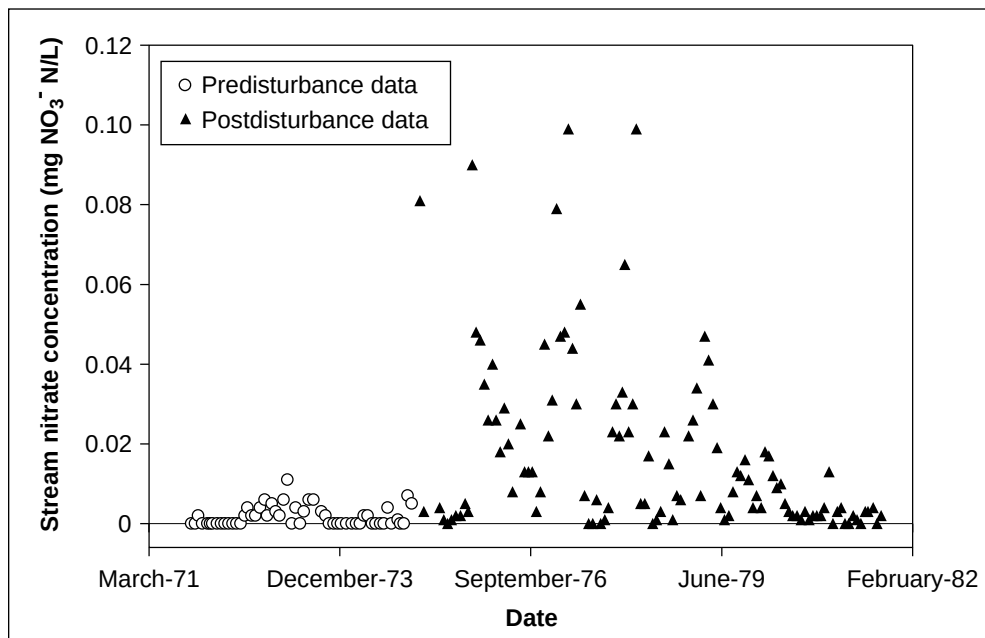


Figure 5.3—Stream nitrate-nitrogen ($\text{NO}_3\text{-N}$) concentration response to the logging and subsequent burning of watershed 6 during 1974–1975. (From: Johnson, and Fredriksen, 2016).

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

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

Carbon Dynamics in Streams

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

Cross-Site and Regional Studies

Synoptic concentrations of nutrients in HJA and broader stream networks—

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

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

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

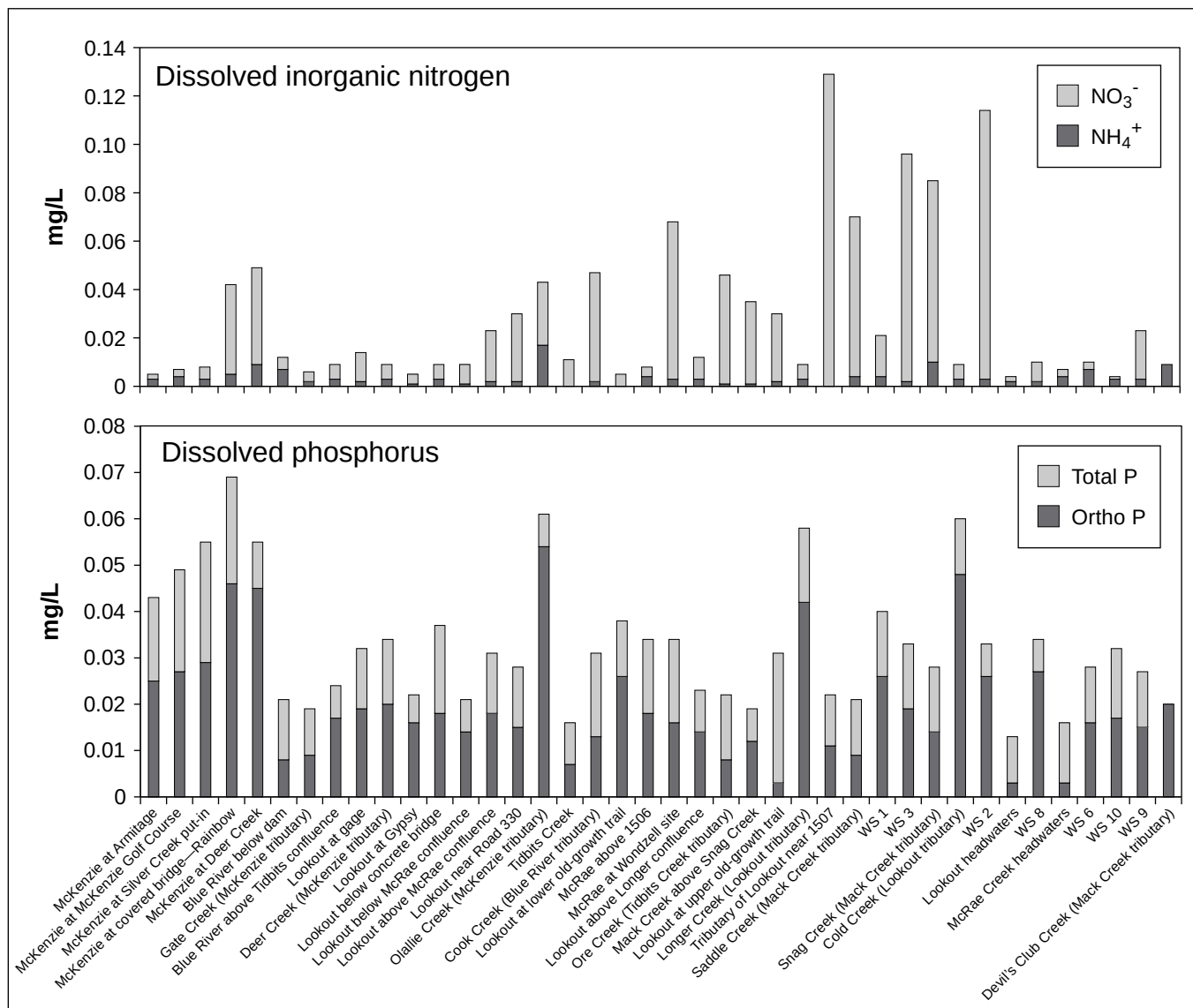


Figure 5.4—Concentrations of dissolved nitrogen (N) and phosphorus (P) during low flow, August 2000, in a range of sizes of streams at the H.J. Andrews Experimental Forest and McKenzie River basin. Sites are arrayed in descending order of upstream drainage area, from largest basin area (3000 km²) on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

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

Lotic Intersite Nitrogen Experiments—

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

Comparison of Trends Over Time in Reference Watersheds

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

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

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

Reliability and Limitations of Findings

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

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

Research Needs

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

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

Potential Utility to Water Quality Regulatory Agencies

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

Key points:

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

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

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

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

Findings From Studies

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

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

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

Dose-Response Studies

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

Reference Watersheds

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

Cross-Site and Regional Studies

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

Responses to Management and Natural Disturbances

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

Reliability and Limitations of Findings

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

Research Needs

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

Potential Utility to Water Quality Regulatory Agencies

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

Key points:

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

Overview and Synthesis

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

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

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

Key points:

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

References

Anderson, N.H.; Sedell, J.R. 1979. Detritus processing by macroinvertebrates in stream ecosystems. *Annual Review of Entomology*. 24: 351–377.

- Andrews Forest 2018.** Web pages of the HJ Andrews Experimental Forest and LTER Site. <https://andrewsforest.oregonstate.edu/>. (15 May 2018).
- Argerich, A.; Haggerty, R.; Johnson, S.L.; Wondzell, S.M.; Dosch, N.; Corson-Rikert, H.; Ashkenas, L.R.; Pennington, R.; Thomas, C.K. 2016.** Comprehensive multiyear carbon budget of a temperate headwater stream. *Journal of Geophysical Research: Biogeosciences*. 121: 1306–1315. doi:10.1002/2015JG003050.
- Argerich, A.; Johnson, S.L.; Sebestyen, S.D.; Rhoades, C.C.; Greathouse, E.; Knoepp, J.D.; Adams, M.B.; Likens, G.E.; Campbell, J.L.; McDowell, W.H.; Scatena F.N.; Ice, G.G. 2013.** Trends in stream nitrogen concentrations for forested reference catchments across the USA. *Environmental Research Letters*. 8: 014039. doi:10.1088/1748-9326/8/1/014039.
- Ashkenas, L.R.; Johnson, S.L.; Gregory, S.V.; Tank, J.L.; Wollheim, W.M. 2004.** A stable isotope tracer study of nitrogen uptake and transformation in an old-growth forest stream. *Ecology*. 85: 1725–1739.
- Bisson, P.A.; Bilby, R.E.; Bryant, M.D.; Dolloff, C.A.; Grette, G.B.; House, R.A.; Murphy, M.L.; Koski, K.V.; Sedell, J.R. 1987.** Large woody debris in forested streams in the Pacific Northwest: past, present, and future. In: Salo, E.O.; Cundy, T.W., eds. *Streamside management: forestry and fishery interactions: proceedings of the symposium*. Seattle, WA: University of Washington, College of Forest Resources: 143–190.
- Cissel, J.H.; Swanson, F.J.; Weisberg, P.J. 1999.** Landscape management using historical fire regimes: Blue River, Oregon. *Ecological Applications*. 9: 1217–1231.
- Compton, J.E.; Church, M.R.; Larned, S.T.; Hogsett, W.E. 2003.** Nitrogen export from forested watersheds in the Oregon Coast Range: the role of N₂-fixing red alder. *Ecosystems*. 6: 773–785.
- Corson-Rikert, H.A. 2014.** Carbon dynamics in the hyporheic zone of a headwater mountain stream in the Cascade Mountains, Oregon. Corvallis, OR: Oregon State University. 132 p. M.S. thesis.
- Cummins, K.W. 1974.** Structure and function of stream ecosystems. *BioScience*. 24: 631–641.
- Cummins, K.W. 1980.** The multiple linkages of forests to streams. In: Waring R.H., ed. *Forests: fresh perspectives from ecosystem analysis. Proceedings of the 40th annual biology colloquium*. Corvallis, OR: Oregon State University Press: 191–198.

- Danehy, R.J.; Bilby, R.E.; Langshaw, R.B.; Evans, D.M.; Turner, T.R.; Floyd, W.C.; Schoenholtz, S.H.; Duke, S.D. 2012.** Biological and water quality responses to hydrologic disturbances in third-order forested streams. *Ecohydrology*. 5: 90–98.
- Dosch, N.T. 2014.** Spatiotemporal dynamics and drivers of stream pCO₂ in a headwater mountain catchment in the Cascade Mountains, Oregon. Corvallis, OR: Oregon State University. 121 p. M.S. thesis.
- Dyrness, C.T. 1969.** Hydrologic properties of soils on three small watersheds in the western Cascades of Oregon. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 111: 16–17.
- Forest Ecosystem Management Assessment Team [FEMAT]. 1993.** Forest ecosystem management: an ecological, economic, and social assessment. Portland, OR: U.S. Department of Agriculture; U.S. Department of the Interior [and others].
- Fradley, C.; Johnson, S.; Li, J. 2007.** Stream macroinvertebrate community responses as legacies of forest harvest at the HJ Andrews Experimental Forest, Oregon. *Forest Science*. 53: 281–293.
- Frear, S.T. 1982.** Ecological benefits of large organic debris in streams. *Forestry Research West*. February 1982: 7–10.
- Fredriksen, R.L. 1969.** A battery powered proportional stream water sampler. *Water Resources Research*. 5: 1410–1413.
- Fredriksen, R.L. 1971.** Comparative chemical water quality: natural and disturbed streams following logging and slash burning. In: Krygier, J.T.; Hall, J.D., ed. *Proceedings of a symposium on forest land uses and stream environment*. Corvallis, OR: Oregon State University, Continuing Education Publications: 125–137.
- Fredriksen, R.L.; Moore, D.G. 1972.** Nutrient retention, mobilization, and loss in undisturbed forest ecosystems on experimental watersheds at the H.J. Andrews Experimental Forest. Internal report 134. Corvallis, OR: U.S. Department of Agriculture, Forest Service. 4 p.
- Gregory, S.V.; Swanson, F.J.; McKee, W.A.; Cummins, K.W. 1991.** An ecosystem perspective of riparian zones: focus on links between land and water. *BioScience*. 41: 540–551.

- Harmon, M.E.; Franklin, F.; Swanson, F.J.; Sollins, P.; Gregory, S.V.; Lattin, J.D.; Anderson, N.H.; Cline, S.P.; Aumen, N.G.; Sedell, J.R.; Lienkaemper, G.W.; Cromack, K., Jr.; Cummins, K.W. 1986.** Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research*. 15: 133–302.
- Hill, B.H.; McCormick, F.H.; Harvey, B.C.; Johnson, S.L.; Warren, M.L.; Elonen, C.M. 2010.** Microbial enzyme activity, nutrient uptake and nutrient limitation in forested streams. *Freshwater Biology*. 55: 1005–1019.
- Holloway, J.M.; Dahlgren, R.A.; Hansen, B.; Casey, W.H. 1998.** Contribution of bedrock nitrogen to high nitrate concentrations in stream water. *Nature*. 395: 785–788.
- Hood, E.; Gooseff, M.N.; Johnson, S.L. 2006.** Changes in the character of stream water dissolved organic carbon during flushing in three small watersheds, Oregon. *Journal of Geophysical Research: Biogeosciences*. 111: G01007.
- Johnson, S.L. 2007.** Storm nutrient dynamics at Andrews Experimental Forest stream gages, 2001 to 2003. Long-Term Ecological Research. Forest Science Data Bank, Corvallis, OR. <http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=CF006>. (13 May 2019). doi:<http://dx.doi.org/10.6073/pasta/809735b6ef217b7c4ab4426f7285401f>.
- Johnson, S.L. 2004.** Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. *Canadian Journal of Fisheries and Aquatic Sciences*. 61: 913–923.
- Johnson, S.L.; Fredriksen, R. 2016.** Precipitation and dry deposition chemistry concentrations and fluxes, Andrews Experimental Forest, 1969 to present. Long-Term Ecological Research. Forest Science Data Bank, Corvallis, OR. <http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=CP002>. (13 May 2019). doi:<http://dx.doi.org/10.6073/pasta/99f51d0a8da29e1c6e10adcad50d499d>.
- Johnson, S.L.; Fredriksen, R. 2017.** Stream chemistry concentrations and fluxes using proportional sampling in the Andrews Experimental Forest, 1968 to present. Long-Term Ecological Research. Forest Science Data Bank, Corvallis, OR. <http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=CF002>. (13 May 2019). doi:<http://dx.doi.org/10.6073/pasta/22cd44c4d8f970fd290371b0604d3d16>.
- Johnson, S.L.; Gregory, S. 2016.** Stream and air temperature data from stream gages and stream confluences in the Andrews Experimental Forest, 1950 to present. Long-Term Ecological Research. Forest Science Data Bank, Corvallis, OR. <http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=HT004>. (13 May 2019). doi:<http://dx.doi.org/10.6073/pasta/11cf1a8de0b8d23cf482a110c77be191>.

- Johnson, S.L.; Jones, J.A. 2000.** Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. *Canadian Journal of Fisheries and Aquatic Sciences*. 57: 30–39.
- Johnson, S.L.; Rothacher, J. 2018.** Stream discharge in gaged watersheds at the Andrews Experimental Forest, 1949 to present. Long-Term Ecological Research. Forest Science Data Bank, Corvallis, OR. <http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=HF004>. (13 May 2019). doi:<http://dx.doi.org/10.6073/pasta/ce70a42e1f637cd430d7b0fb64faefb4>.
- Johnson, S.L.; Swanson, F.J.; Grant, G.E.; Wondzell, S.M. 2000.** Riparian forest disturbances by a mountain flood—the influence of floated wood. *Hydrological Processes*. 14: 3031–3050.
- Jones, J.A.; Grant, G.E. 1996.** Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. *Water Resources Research*. 32: 959–974.
- Jones, J.A.; Grant, G.E. 2001.** Comment on ‘Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon’ by J.A. Jones and G.E. Grant. *Water Resources Research*. 37: 179–180.
- Kane, E.S.; Betts, E.F.; Burgin, A.J.; Clilverd, H.M.; Crenshaw, C.L.; Fellman, J.B.; Myers-Smith, I.H.; O'Donnell, J.A.; Sobota, D.J.; van Verseveld, W.J.; Jones, J.B. 2008.** Precipitation control over inorganic nitrogen import—export budgets across watersheds: a synthesis of long-term ecological research. *Ecohydrology*. 1: 105–117.
- Kasahara, T.; Wondzell, S.M. 2003.** Geomorphic controls on hyporheic exchange flow in mountain streams. *Water Resources Research*. 39: 1005. doi:10.1029/2002WR001386.
- Levno, A.B.; Rothacher, J.S. 1967.** Increases in maximum stream temperatures after logging in old-growth Douglas-fir watersheds. Res. Note PNW-65. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 12 p.
- Lienkaemper, G.W.; Swanson, F.J. 1987.** Dynamics of large woody debris in streams in old-growth Douglas-fir forests. *Canadian Journal of Forest Research*. 17: 150–156.
- Likens, G.E.; Bormann, F.H.; Johnson, N.M.; Fisher, D.W.; Pierce, R.S. 1970.** Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. *Ecological Monographs*. 40: 23–47.

- Long Term Ecological Research Network [LTER Network]. 2013.** Climate and hydrology data base projects: CLIMDB/HYDRODB. <http://climhy.lternet.edu/>. (24 May 2019).
- Martin, C.W.; Harr, R.D. 1988.** Precipitation and streamwater chemistry from undisturbed watersheds in the Cascade Mountains of Oregon. *Water, Air, and Soil Pollution*. 42: 203–219.
- Martin, C.W.; Harr, R.D. 1989.** Logging of mature Douglas-fir in western Oregon has little effect on nutrient output budgets. *Canadian Journal of Forest Research*. 19: 35–43.
- McClellan, M.H. 1988.** Denitrification potentials in forest riparian soils of the western Oregon Cascades: spatial and temporal variation. Corvallis, OR: Oregon State University. 106 p. M.S. thesis.
- McGuire, K.J.; McDonnell, J.J.; Weiler, M.; Kendall, C.; McGlynn, B.L.; Welker, J.M.; Seibert, J. 2005.** The role of topography on catchment-scale water residence time. *Water Resources Research*. 41: W05002. doi:10.1029/2004WR003657.
- McKee, A; Johnson, S.L. 2017.** National Atmospheric Deposition (NADP) at Site OR10; Precipitation chemistry at the HJ Andrews Experimental Forest. Long-Term Ecological Research. Forest Science Data Bank, Corvallis, OR. [Database CP001]. <http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=CP001>. (13 May 2019).
- Mulholland, P.; Dahm, C.; Dodds, W.; Gregory, S.; Grimm, N.; Hall, R.; Hamilton, S.; Johnson, S.; Peterson, B.; McDowell, W.; Meyer, J.; Tank, J.; Valett, H.; Webster, J. 2015.** Lotic Intersite Nitrogen eXperiment II (LINX II): a cross-site study of the effects of anthropogenic land use change on nitrate uptake and retention in 72 streams across 8 different biomes (2003–2006). Lotic Intersite Nitrogen Experiment. Forest Science Data Bank, Corvallis, OR. [Database AN006]. <http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=AN006> (13 May 2019) DOI:<http://dx.doi.org/10.6073/pasta/eac34b6c1cfb0268dd76ef68a7a90bfc>.
- Mulholland, P.J.; Helton, A.M.; Poole, G.C.; Hall, R.O., Jr.; Hamilton, S.K.; Peterson, B.J.; Tank, J.L.; Ashkenas, L.R.; Cooper, L.W.; Dahm, C.N.; Dodds, W.K.; Findlay, S. G.; Gregory, S.V.; Grimm, N.B.; Johnson, S.L.; McDowell, W.H.; Meyer, J.L.; Valett, H.M.; Webster, J.R.; Arango, C.P.; Beaulieu, J.J.; Bernot, M.J.; Burgin, A.J.; Crenshaw, C.L.; Johnson, L.T.; Niederlehner, B.R.; O'Brien, J.M.; Potter, J.D.; Sheibley, R.W.; Sobota, D.J. 2008.** Stream denitrification across biomes and its response to anthropogenic nitrate loading. *Nature*. 452: 202–205.

- National Atmospheric Deposition Program [NADP]. 2019.** NTN [National Trends Network] Site OR10. HJ Andrews Experimental Forest. <http://nadp.slh.wisc.edu/data/sites/siteDetails.aspx?net=NTN&id=OR10>. (1 July 2019).
- Munn, N.L.; Meyer, J.L. 1990.** Habitat-specific solute retention in two small streams: an intersite comparison. *Ecology*. 71: 2069–2082.
- Oregon State University. 2017.** StreamChemDB. <http://web.fsl.orst.edu/streamchem/>. (1 November 2020).
- Oregon State University. 2018.** Cooperative Chemical Analytical Lab (CCAL) <http://ccal.oregonstate.edu/>. (15 May 2018).
- Peterson, B.J.; Wollheim, W.M.; Mulholland, P.J.; Webster, J.R.; Meyer, J.L.; Tank, J.L.; Martí, E.; Bowden, W.B.; Valett, H.M.; Hershey, A.E.; McDowell, W.H.; Dodds, W.K.; Hamilton, S.K.; Gregory, S.V.; Morrallet, D.D. 2001.** Control of nitrogen export from watersheds by headwater streams. *Science*. 292: 86–90.
- Post, D.A.; Jones, J.A. 2001.** Hydrologic regimes of forested, mountainous, headwater basins in New Hampshire, North Carolina, Oregon, and Puerto Rico. *Advances in Water Resources*. 24: 1195–1210.
- Rothacher, J.S.; Dyrness, C.T.; Fredriksen, R.L. 1967.** Hydrologic and related characteristics of three small watersheds in the Oregon Cascades. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 54 p.
- Ryan, D.F.; Calhoun, J.M., tech. eds. 2010.** Riparian adaptive management symposium: a conversation between scientists and management. Gen. Tech. Rep. PNW-GTR-830. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 135 p.
- Sedell, J.R.; Bisson, P.A.; Swanson, F.J.; Gregory, S.V. 1988.** What we know about large trees that fall into streams and rivers. In: Maser, C.; Tarrant, R.F.; Trappe, J.M.; Franklin, J.F., eds. *From the forest to the sea: a story of fallen trees*. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; U.S. Department of the Interior, Bureau of Land Management: 47–81.
- Sedell, J.R.; Dahm, C.N. 1990.** Spatial and temporal scales of dissolved organic carbon in streams and rivers. In: *Organic acids in aquatic ecosystems: Dahlem workshop report 1990*. New York: John Wiley & Sons Ltd.: 261–279.
- Sobota, D.J.; Johnson, S.L.; Gregory, S.V.; Ashkenas, L.R. 2012.** A stable isotope tracer study of the influences of adjacent land use and riparian condition on fates of nitrate in streams. *Ecosystems*. 15: 1–7.

- Sollins, P.; McCorison, F.M. 1981.** Nitrogen and carbon solution chemistry of an old growth coniferous forest watershed before and after cutting. *Water Resources Research*. 17: 1409–1418.
- Sullivan, K.; Lisle, T.E.; Dolloff, C.A.; Grant, G.E.; Reid, L.M. 1987.** Stream channels: the link between forests and fishes. In: Salo, E.O.; Cundy, T.W., eds. *Streamside management: forestry and fishery interactions*. Institute of Forest Resources Contribution 57. Seattle, WA: University of Washington, Institute of Forest Resources: 39–97.
- Swanson, F.J.; Fredriksen, R.L.; McCorison, F.M. 1982a.** Material transfer in a western Oregon forested watershed. In: Edmonds, R.L., ed. *Analysis of coniferous forest ecosystems in the western United States*. Stroudsburg, PA: Hutchinson Ross Publishing Company: 233–266.
- Swanson, F.J.; Gregory, S.V.; Sedell, J.R.; Campbell, A.G. 1982b.** Land-water interactions: the riparian zone. In: Edmonds, R.L., ed. *Analysis of coniferous forest ecosystems in the western United States*. Stroudsburg, PA: Hutchinson Ross Publishing Company: 267–291.
- Swanson, F.J.; Johnson, S.L.; Gregory, S.V.; Acker, S.A. 1998.** Flood disturbance in a forested mountain landscape. *BioScience*. 48: 681–689.
- Swanson, F.J.; Lienkaemper, G.W.; Sedell, J.R. 1976.** History, physical effects, and management implications of large organic debris in western Oregon streams. Gen. Tech. Rep. PNW-GTR-056. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 15 p.
- Triska, F.J.; Cromack, K., Jr. 1980.** The role of wood debris in forests and streams. In: Waring, R.H., ed. *Forests: fresh perspectives from ecosystem analysis*. Proceedings of the 40th annual biology colloquium. Corvallis, OR: Oregon State University Press: 171–190.
- Triska, F.J.; Sedell, J.R.; Cromack, K., Jr.; Gregory, S.V.; McCorison, F.M. 1984.** Nitrogen budget for a small coniferous forest stream. *Ecological Monographs*. 54: 119–140.
- Vanderbilt, K.L.; Lajtha, K.; Swanson, F.J. 2003.** Biogeochemistry of unpolluted forested watersheds in the Oregon Cascades: temporal patterns of precipitation and stream nitrogen fluxes. *Biogeochemistry*. 62: 87–117.
- Vannote, R.L.; Minshall, G.W.; Cummins, K.W.; Sedell, J.R.; Cushing, C.E. 1980.** The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences*. 37: 130–137.

- van Verseveld, W.J.; McDonnell, J.J.; Lajtha, K. 2008.** A mechanistic assessment of nutrient flushing at the catchment scale. *Journal of Hydrology*. 358: 268–287.
- van Verseveld, W.J.; McDonnell, J.J.; Lajtha, K. 2009.** The role of hillslope hydrology in controlling nutrient loss. *Journal of Hydrology*. 367: 177–187.
- Ward, G.M.; Aumen, N.G. 1986.** Woody debris as a source of fine particulate organic matter in coniferous forest streams ecosystems. *Canadian Journal of Fisheries and Aquatic Sciences*. 43: 1635–1642.
- Wise, D.R.; Johnson, H.M. 2011.** Surface water nutrient conditions and sources in the United States Pacific Northwest. *JAWRA Journal of the American Water Resources Association*. 47: 1110–1135.
- Wondzell, S.M. 2011.** The role of the hyporheic zone across stream networks. *Hydrological Processes*. 25: 3525–3532.
- Wondzell, S.M.; Swanson, F.J. 1996a.** Seasonal and storm dynamics of the hyporheic zone of a 4th-order mountain stream. I: Hydrologic processes. *JNABS*. 15: 3–19.
- Wondzell, S.M.; Swanson, F.J. 1996b.** Seasonal and storm dynamics of the hyporheic zone of a 4th-order mountain stream. II: Nitrogen cycling. *Journal of the North American Benthological Society*. 15: 20–34.
- Wondzell, S.M.; Swanson, F.J. 1999.** Floods, channel change, and the hyporheic zone. *Water Resources Research*. 35: 555–567.
- Yano, Y.; Lajtha, K.; Sollins, P.; Caldwell, B.A. 2005.** Chemistry and dynamics of dissolved organic matter in a temperate coniferous forest on andic soils: effects of litter quality. *Ecosystems*. 8: 286–300.