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

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Introduction

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

Site Description

TCEF (lat. 46° 55' N, long. 110° 55' W) is in the Little Belt Mountains, within the Lewis and Clark National Forest in central Montana. Tenderfoot Creek drains this third-order watershed, 22.8 km^2 in total area, comprising eight first- or second-order subwatersheds ranging in size from 3 to 22.8 km^2 (fig. 6.1) (Jencso et al. 2009). Topography is mountainous and ranges in elevation from 1840 to 2420 m (Pacific et al. 2009).

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

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

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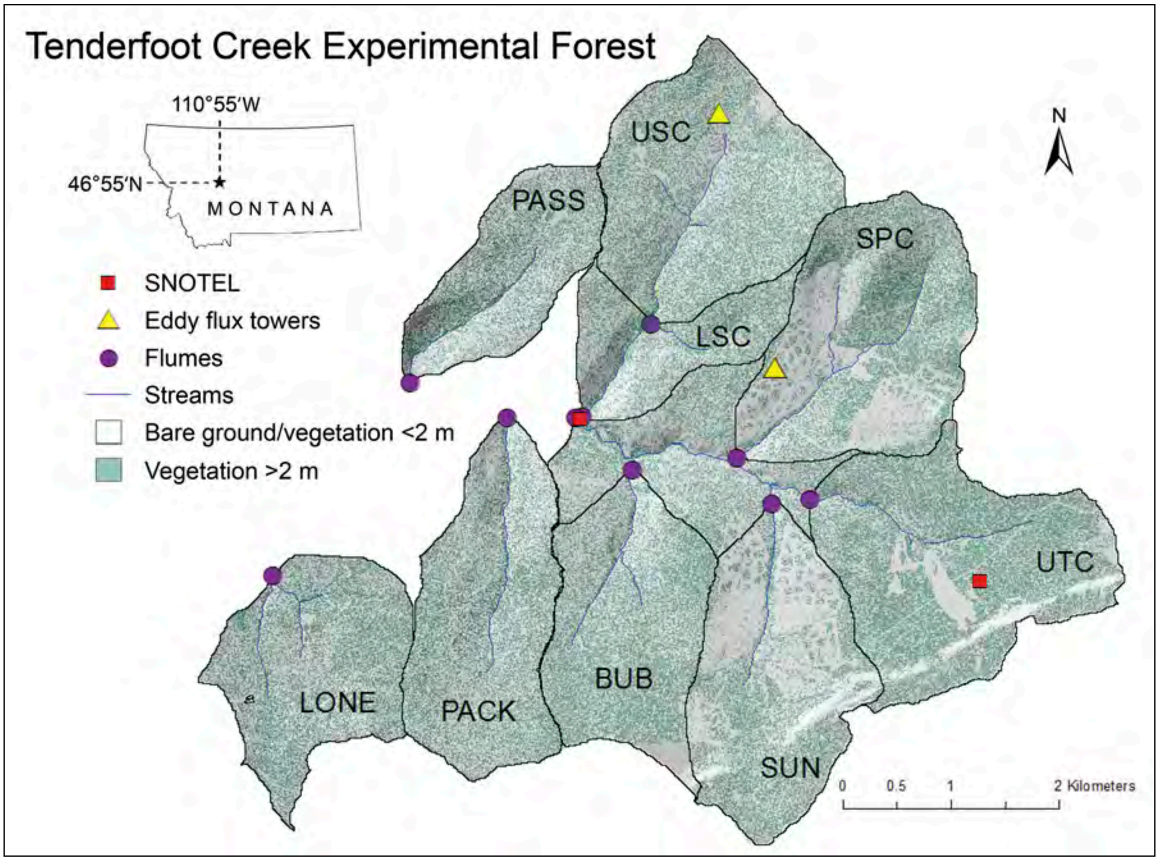

Figure 6.1—Tenderfoot Creek Experimental Forest. Locations of snow telemetry (SNOTEL), eddy flux towers, and flume gaging stations are shown against the vegetation coverage. Following are eight subwatersheds that are monitored with stream gages: Passion Creek (PASS), Upper and Lower Stringer Creek (USC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

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

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

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

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

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

Research History

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

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

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

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

Biological Responses to Stream Nutrients N and P

Issues of Concern

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

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

Findings From Studies

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

Because TCEF remains largely undisturbed biogeochemically, there are no published studies specifically examining the response of the biotic community at TCEF to N and P enrichment. Studies have primarily focused on understanding how watersheds translate rainfall and snowmelt into runoff and on investigating the influence of complex topography and climate variability on streamflow, solute export, and atmosphere-land exchange. The USFS has monitored major cation and anion concentrations in stream water at the outlet of all subwatersheds at TCEF approximately biannually from 1992 to 2009 and from 2014 to present. Mean annual stream water concentrations of N (10 to 20 µg NO_3^--N/L) and P (30 to 40 µg PO_4^{3-}-P/L) have been generally low, as is typical in relatively undisturbed headwaters in this region (McCaughey et al. 2010). High temporal frequency, in situ sensors, deployed in 2013 by the authors, revealed the complex nature of stream solute dynamics, including diel concentration swings and snowmelt pulses within observed seasonal and annual patterns not captured previously by biannual or quarterly grab sampling.

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

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

Landscape hydrodynamics—

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

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

Several studies by Jensco et al. (2009, 2010) and Jencso and McGlynn (2011) demonstrated the important role of landscape structure in mediating hillslope hydrologic connectivity. Simple metrics such as the size of the upslope contributing area, or upslope accumulated area (UAA), can explain the extent of hillslope-riparian-stream (HRS) connectivity in a watershed. Watersheds that have a high proportion of large UAA hillslopes exhibit higher levels of HRS hydrologic connectivity, and supply a more constant flux of terrestrial solutes from hillslopes to streams than do topographically complex watersheds with a smaller proportion of large UAA hillslopes (Smith et al. 2013).

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

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

Climate variability is another important driver of terrestrial hydrodynamics and solute loading. A study from TCEF by Nippgen et al. (2011) found that interwatershed variation in topographic indices, which are metrics of the average amount of time it takes for a precipitation input to be translated into a runoff output, explained the variability in mean response time of watersheds at TCEF. Runoff ratios within a given catchment were strongly correlated with topographic indices describing the watershed's structure, such as the degree of convergence, distance from creek, gradient to creek, convergent area, and riparian buffering capacity. Runoff rations for individual basins do not reflect larger scale climate metrics, such as maximum snow-water equivalent (SWE). In contrast, climate variability was an important driving factor in controlling intrawatershed variability in runoff.

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

Land-atmosphere interactions—
Topographic-driven water redistribution affects solute export from the terrestrial ecosystem, and also exerts a strong control on the generation of solutes via soil biogeochemical processes. For example, soil carbon dioxide (CO_2) efflux is a product of aerobic soil respiration and mineralization of organic matter, and thus can be viewed as an indicator of soil biological processes. While not a direct measure of nutrient cycling in soils, landscape-level variation in CO_2 fluxes can indicate locations and periods of active nutrient cycling and microbial decomposition.

Extensive work by Pacific et al. (2008, 2009, 2011), Riveros-Iregui et al. (2011, 2012), Riveros-Iregui and McGlynn (2009), and Emanuel et al. (2011) investigated the central role of landscape complexity in determining the spatial and interannual variability of soil CO_2 fluxes. In studies of Stringer Creek subwatershed (fig. 6.1), the highest soil CO_2 fluxes were observed in riparian sites with consistently high soil moisture and high UAA values (Riveros-Iregui and McGlynn 2009). Hillslope positions with low soil moisture and low UAA values were characterized by low soil CO_2 flux rates. Soil CO_2 concentrations were correspondingly higher in the riparian zones than in the hillslopes and correlated with higher soil water content (Pacific et al. 2008). Cumulative soil CO_2 fluxes across the growing season were highest in riparian areas with high UAA and gentle slopes, where groundwater tables were present throughout the entire growing season (Pacific et al. 2011). These findings were evidence that topographically driven water redistribution, and subsequent soil water availability, is an important driver of the spatial patterns of soil microbial processes within the landscape.

Climate forcing, expressed as interannual variation in water availability, can also explain temporal trends in soil CO_2 fluxes. In lowlands and riparian areas with high UAA values, cumulative soil respiration was 24 percent lower in wet years than dry years (Pacific et al. 2009, Riveros-Iregui et al. 2012). In contrast, hillslope positions with low UAA values exhibited higher soil respiration in wet years compared to dry years. This bidirectional behavior of soil respiration in response to a single climatic or hydrologic forcing suggests that under a wetter climate some portions of the watershed became a stronger carbon source, while other portions of the watershed became a weaker source. This bidirectional behavior probably produced a more muted response to climate variability from the watershed as a whole (Pacific et al. 2009, Riveros-Iregui et al. 2012).

Instream dynamics—

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

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

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

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

Reference Watersheds

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

Although watersheds at TCEF have been minimally disturbed to date, the USFS charter for TCEF does not officially designate that these sites be maintained as reference watersheds. The charter allows for timber harvesting associated with research activities, so some sites currently functioning as potential regulatory reference sites might have trees cut or be otherwise manipulated for research in the future. In that case, their streams might no longer meet the strictest Montana DEQ reference benchmark (Tier 1: natural condition), but, depending on the degree of disturbance to plants and soils, might qualify as Tier 2 reference sites with minimally affected conditions (Suplee et al. 2005). If the USFS revised the TCEF charter to designate one or more subwatersheds to remain permanently with minimal onsite human disturbance, it would assure that benchmark reference streams for regulatory purposes would be maintained into the future. In addition, establishing reference basins at TCEF would enhance the scientific value of future studies at this site by providing a reliable internal reference, against which long-term effects on streams of experimental treatments could be compared.

Dose-Response Studies

No dose-response studies have been conducted at TCEF.

Cross-Site and Regional Studies

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

Responses to Management and Natural Disturbances

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

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

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

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

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

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

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

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

Natural disturbance regimes—

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

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

Reliability and Limitations of Findings

Research at TCEF is based on more than a decade of extensively field-based, spatially distributed empirical data with high temporal resolution. Findings based on these data are highly reliable and are an accurate portrayal of hydrologic response in relatively undisturbed, forested headwater sites with mountainous terrain and snowmelt-dominated hydrologic regimes. As an experimental forest for the past 50 years, land management at TCEF has been closely controlled.

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

Research Needs

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

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

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

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

Potential Utility to Water Quality Regulatory Agencies

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

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

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

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

Key points:

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

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

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

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

Findings From Studies

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

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

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

Reference Watersheds

Semiannual monitoring of stream water concentrations of nutrients other than N and P has been conducted by the USFS since 1992 at Stringer Creek, Upper Tenderfoot Creek, and Bubbling Creek, where these streams drain de facto reference watersheds (fig. 6.1). As we stated earlier, undisturbed, instrumented watersheds at TCEF with long-term data records are rare and of high value to the regulatory community for establishment of baseline conditions. The USFS monitoring dataset at TCEF is an important resource for managers seeking to establish baseline conditions in undisturbed, reference watersheds.

Dose-Response Studies

No dose-response studies have been conducted at TCEF.

Cross-Site and Regional Studies

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

Responses to Management and Natural Disturbances

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

Reliability and Limitations of Findings

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

Research Needs

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

Potential Utility to Water Quality Regulatory Agencies

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

Key points:

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

Overview and Synthesis

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

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

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

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

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