In: Proceedings 2nd Interagency Conference on Research in the Watersheds. May 15-18 2006; Coweeta Hydrologic Lab., Otto, NC. pp 3-21.

DISTURBANCE AND WATER RELATED RESEARCH IN THE WESTERN UNITED STATES

Kelly Elder, Kate Dwire, Robert Hubbard, Charles Rhoades, Sandra Ryan, Mike Young, Laurie Porth, Mark Dixon and Angus Goodbody

Rocky Mountain Research Station, USDA Forest Service, 240 West Prospect Road, Fort Collins, CO 80526

Abstract—Water plays a critical role in agriculture, energy, recreation, conservation, transportation, and indeed, life in the western United States. Water supply and variability in supply was paramount even before European settlers moved into the region. As demands on water have increased with time, all water related issues have also increased in importance to civilization. Water quantity issues drive western economics, politics, and demographics. Disturbance affects water quantity because precipitation and water use are controlled in part by land cover. The biogeochemical controls on water quality are closely tied to water quantity, but are also affected by landscape variability and both natural and anthropogenic disturbance. Slow recovery of forest vegetation may prolong the disturbance impacts on water quality in arid western basins compared to their relatively moist eastern counterparts. Sedimentation is a common cause of water quality impairment in actively managed landscapes. Riparian areas provide critical buffers to aquatic ecosystems from upland disturbances and may be integrators, magnifiers, or filters depending on the state of both the upland and riparian systems. Fisheries attract more attention than other aquatic resources and management of western water systems has had widespread impacts on fish habitat and populations. A general review of western issues with a Rocky Mountain and Fraser Experimental Forest focus is provided for water quantity, quality, fluvial, riparian and native fisheries issues.

INTRODUCTION

Few would argue that water is the most critical natural resource in the western United States. For over a century water has been the foci of conflict and failure, survival and success on western lands. The Colorado River basin dominates the landscape of the western U.S. and shares characteristics with other major western water courses such as the Columbia, Missouri, and Rio Grande. These characteristics include high-elevation headwaters dominated by snow, long distances to ocean bodies flowing through arid regions, high demands on supply highlighted by over-appropriated water resources, and substantial agricultural requirements conflicting with increasing municipal and industrial demands. Western basins are also largely administered by government entities. Ownership of land area in the Colorado basin, for example, is only 19% private, with 56% federal, and 25% state and Indian (Weatherford and Brown 1991). These government lands, particularly the federally managed areas, are also the primary water source areas because they tend to be the upper-elevation forested regions that receive the greatest annual precipitation.

Headwaters of mid-latitude, western rivers systems are located in the Rocky Mountain cordillera, mountains of the basin and range region, Sierra Nevada, and coastal ranges. These physiographic features are particularly effective in producing the orographics that lead to higher precipitation rates than observed in nearby lowland regions. Northern hemisphere circulation produces moist westerly air mass flows from the Pacific that collide with these orographic barriers and the circulation is such that most of the precipitation comes as snowfall during the fall, winter and spring months. The end result is that the majority of annual precipitation for much of the region, as much as 75%, is stored in winter snowpacks in mountain regions. Potential evapotranspiration is also reduced at higher elevations due to cooler temperatures and limited growing seasons. These forested and alpine regions produce as much as 90% of the annual runoff as the snow melts in the spring and early summer. Because these source areas are largely federally managed, factors affecting the accumulation and subsequent ablation of the snowpack, as well as on-site consumptive use of water, place great pressure on agencies responsible for the source areas. As water resources become more limited due to increasing demand, the federal agencies managing the source areas are placed in a role of increasing conflict with multiple users with varied needs. Climate variability, recent prolonged droughts in particular, has accelerated both the demand and conflict in managing the resource. Management decisions must include consideration of downstream users' water rights, recreation, threatened and endangered species, in-stream flows, sedimentation, fire

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and fuels management, forest production, fisheries and wildlife, hydroelectric power generation, among others.

This paper briefly discusses western water issues from the perspective of research on streamflow generation from headwaters catchments, water quality, sediment production, riparian habitats, and native fisheries. We discuss the broad western context of these issues and focus on Colorado and the Fraser Experimental Forest (FEF), where much of the authors' contemporary research is located. Past, current and future research on these issues are discussed.

WATER QUANTITY

Water supply in western watersheds follows natural cycles closely related to continental scale atmospheric forcings. In time of above-normal precipitation, the West enjoys ample supply in most regions. Low precipitation regimes affect almost all human endeavors negatively. Storage projects have ameliorated short-term deficits to some degree, but the time scale of many drought cycles exceeds storage capacity. In recent decades the construction of additional storage facilities has largely fallen out of favor for many reasons and efforts to increase runoff have centered on increasing wintertime snowpack storage and reducing summertime transpiration losses. Researchers have shown that runoff from headwater basins may be altered by changing the vegetation within the basin. Almost a century ago in southern Colorado, Bates and Henry (1928) conducted the first paired watershed study in the world at Wagon Wheel Gap and found that a reduction in forest cover produced an increase in local streamflow. Subsequent studies have refined our understanding of the processes that lead to increased streamflow with decreased forest cover. Bosch and Hewlett (1982) and MacDonald and Stednick (2003) summarize much of the research conducted over the last century on treated watersheds in the western U.S.

Much of our current understanding of the effects of forest management on runoff in the subalpine zone comes from studies conducted at the Fraser Experimental Forest since its establishment in 1937 near Fraser, Colorado (e.g. Wilm and Dunford 1948, Anderson and others 1976, Troendle 1983, Troendle and King 1985, Schmidt and Troendle 1989, Schmidt and others 1998). The FEF is a generally north-facing subalpine basin dominated by lodgepole (*Pinus contorta*), Engelmann spruce (*Picea engelmanii*), subalpine fir (*Abies lasiocarpa*), and some aspen (*Populus tremuloides*), with elevations ranging from about 2680 m a.s.l. (8800') to 3900 m (12,800'). The basin has a snow-dominated hydrological regime, with 70-80% of the annual precipitation falling as snow and about 90% of the annual runoff derived from melting snow.

Results from the Fool Creek paired watershed study within the Experimental Forest were first reported by Goodell (1958) who found that clear cutting 40% of the basin in alternate cut-leave patches produced a marked increase in annual flow when compared to the adjacent East St. Louis control watershed. Troendle and King (1985) later showed the long-term effect after revisiting the 28-year post harvest period. They observed a sustained average effect of increased streamflow of 82 mm (40%) resulting from increased snowpack accumulation of 28 mm (9%) water equivalent and reduced summertime losses. Increased snowpack results from reduced interception of snowfall by the canopy, of which a significant percentage is subsequently lost to sublimation before it can be incorporated into the snowpack. Removing the canopy allows snowfall to accumulate directly to the snowpack, which is then stored with only small losses until it melts and is available for runoff. Canopy removal also reduces summertime losses due to transpiration and plant depletion of soil moisture, resulting in increased runoff. Troendle and King also observed that peak flows occurred 7.5 days earlier with a 23% increase in the peak flow on average, over the period. Finally, they predicted a time to hydrologic recovery after treatment of approximately 70 years based on the regression relationship developed for the 28 year period.

Elder and others (in preparation) have examined the continuous long-term Fool Creek record though the 2005 water year, giving 49 years for post-treatment analyses (Figure 1). Results show that differences in snowpack water equivalent are no longer statistically significant. However, annual streamflow still shows a 60 mm (29%) increase on average over the 49 year period. Peak flows still arrive 7 days earlier than the pre-harvest period, but peak flow volume has been reduced to a 16% increase over the calibration period. The time to hydrologic recovery has dropped markedly from 70 years to slightly less than 60 years

(Figure 2). This shorter predicted recovery time may be influenced in part by recent drought conditions observed in the last decade (Figure 1).

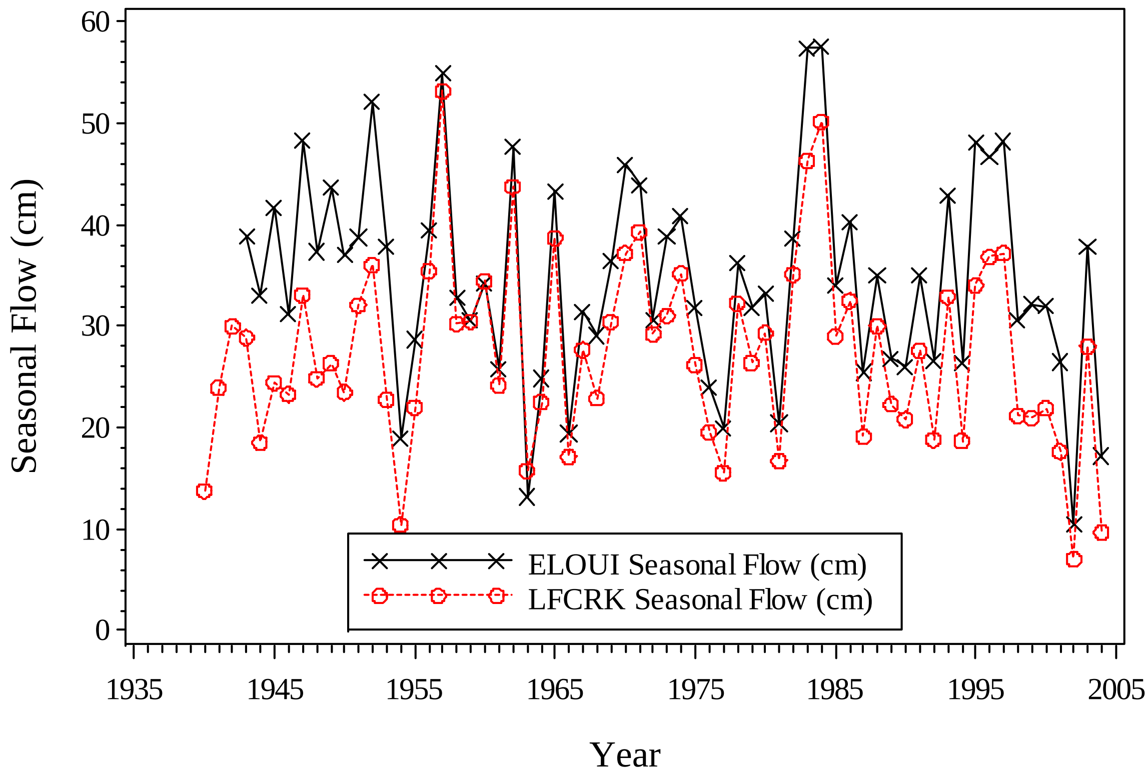

Figure 1. Unit area discharge record for the Fool Creek (1940-2004) and East St. Louis (1943-2004) paired watershed experiment. Treatment was completed in 1956.

In addition to changes in the annual water yield, changes in the seasonal snowmelt hydrograph were documented following forest harvest. The primary change in the annual snowmelt hydrograph comes during the rising limb, with no significant change in the falling limb. The rising limb from the subalpine region occurs between the beginning of May and the middle of June. Increased yields following harvest are also three to four times greater on wet years than dry years when deficits are greatest. From a water manager's perspective, these factors show that increased flow occurs during the season of little need, which means that additional water storage must be constructed to realize the benefits of higher water yields.

There are still a number of open questions related to water supply in western watersheds. Because runoff is controlled by a snow-dominated hydrological regime, better understanding of snow-related hydrological processes offers the greatest potential for effectively managing watersheds. Additional studies are needed on spatial variability of snow accumulation and melt processes, vegetation effects on snow accumulation, climate variability and its effect on snow processes, and hydrologic pathways from the snowpack surface through the snowpack, the soil matrix and into the stream channel. The hydrologic consequences of extensive conifer mortality caused by bark beetle and other insects represent another critical unknown. Millions of acres are currently infested by mountain pine beetle (MPB) resulting in substantial overstory mortality in large watersheds. Tree mortality caused by mechanical harvesting, insect or disease all change the hydrologic cycle similarly, so one might expect a commensurate increase in water yield following the current outbreak. However, similarity between disturbance effects depends on many factors such as extent of impact, forest species composition, forest structure, residual vegetation, local climatic regime, etc. One important question is whether the residual stand will simply use excess water on site. Better understanding of tree water use, both in disturbed and undisturbed scenarios will help answer this question. Transpirational water use has traditionally been a weak area in our understanding of basic water balance at the stand, hillslope and watershed scale.

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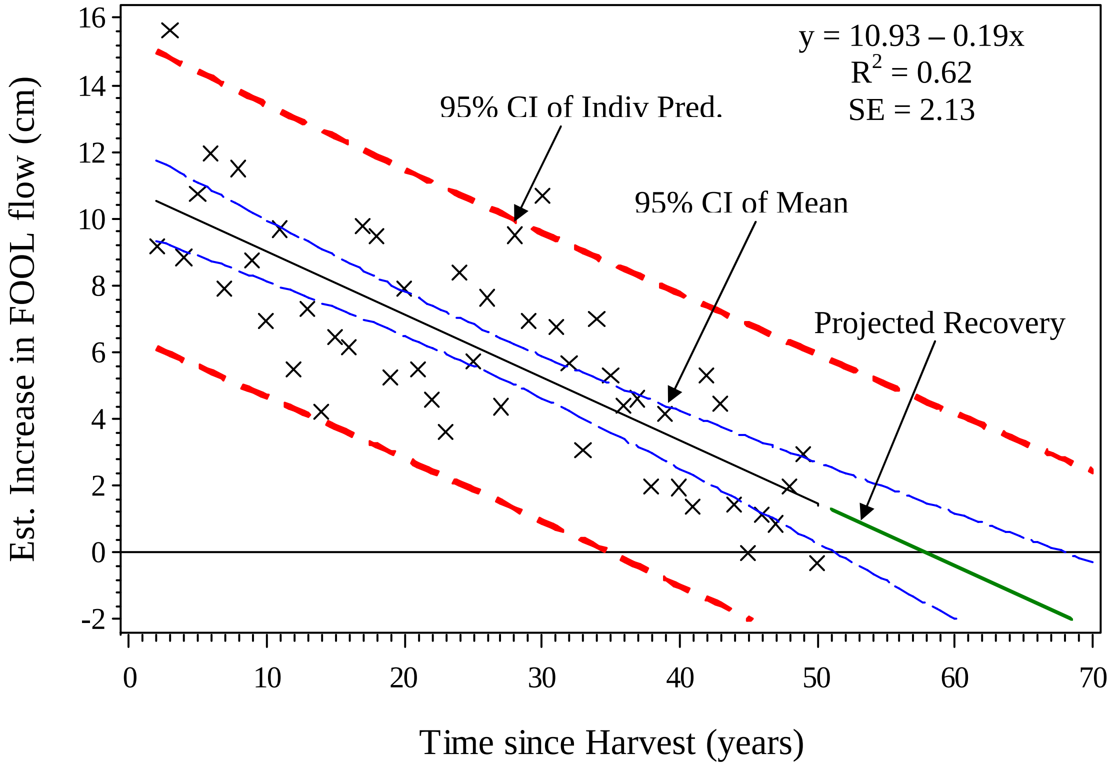

Figure 2. Regression of expected increase in Fool Creek yield based on the pretreatment calibration period versus observed yield since the clear cut treatment was completed in 1956.

Transpiration in Rocky Mountain Forests

Rocky Mountain Forests are characterized by relatively extreme environments ranging from cold, moist high elevation settings to lower elevation forests where persistent water deficits exist throughout much of the growing season. Consequently, water and temperature are the primary environmental factors limiting tree growth and water use in Rocky Mountain forests. Understanding how species respond to and cope with these environmental factors is critical for accurate models of site water balance and for developing mechanistic models of how forests will respond to disturbance, climate and management scenarios.

Plant water use and productivity are inextricably linked because under photosynthetic conditions, stomata operate to both enhance photosynthesis and avoid dehydration induced damage. As plants open stomata to acquire CO_2 for photosynthesis, water is pulled from the soil to the leaf via the water potential gradient that exists between the air at the leaf surface and the soil. As a result, plant water status during photosynthesis is regulated to permit the transpiration that necessarily accompanies stomatal opening, and is kept from falling below damaging levels to prevent disruption of function. A species' ability to balance the uptake of carbon for growth and metabolism with water loss via transpiration ultimately determines their productivity and survival, especially in arid and semi arid environments.

It is well recognized that stomata play a critical role in regulating plant water status in terrestrial vegetation but despite decades of research, the actual mechanism remains unclear. A large body of work has shown convincing, yet sometimes conflicting evidence that stomata respond to a variety of water relationship parameters under light-saturating conditions. Stomatal response has been linked to humidity (Mott and Parkhurst 1991), transpiration (Cowan 1995; Franks and others 1997; Mott and Buckley 1998), soil moisture (Loewenstein and Pallardy 1998; Tardieu and Simonneau 1998), and hydraulic conductance, and actual response mechanisms have been investigated for humidity, transpiration and soil moisture. Recent work suggests that the actual stomatal response mechanism is closely related to changes in the hydraulic conductance of the flow path (Hubbard and others 2001) and that stomatal control is achieved at the guard cells through a hydraulically-mediated feedback (Buckley 2005). This type of control is consistent with most of the current and past research and remains the most plausible explanation for a universal mechanism.

Conifer species dominate most Rocky Mountains forest communities. Conifers are well suited to soil water deficits that prevail through much of the growing season in the region. In general, conifer species exhibit tight control of stomatal opening to prevent stem and leaf water potential from falling below critical levels leading to cavitation of the water column. Other factors that facilitate growth and survival of Rocky Mountain conifers include the physiological adjustments of hydraulic architecture and the ratio of transport tissues to leaf area.

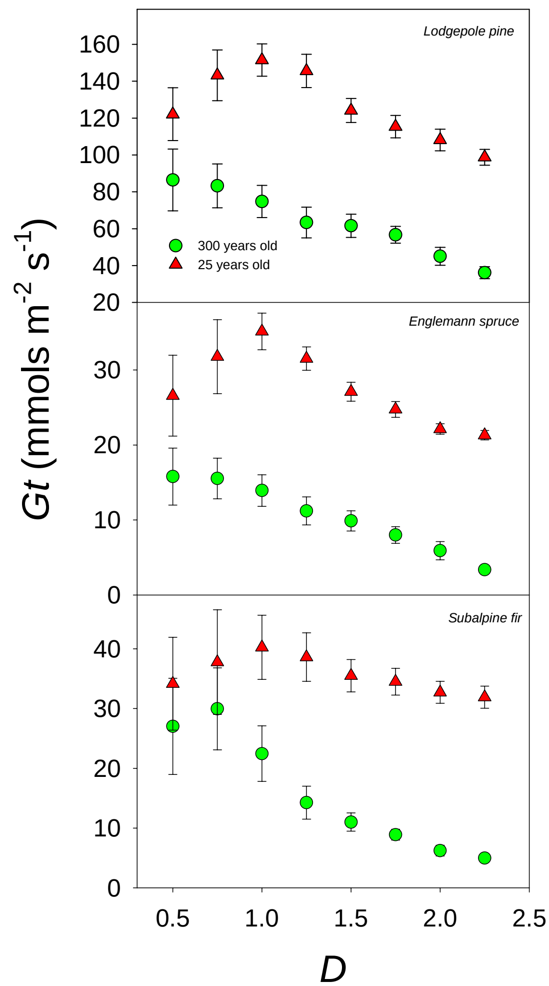

Figure 3. Canopy conductance versus air saturation deficit for the dominant tree species in 300 and 25 year old stands at FEF.

Although most tree species in the Rocky Mountain region exhibit tight stomatal control of leaf gas exchange, the degree and timing varies significantly among sites and species. Pataki and others (2000) showed that four common Rocky Mountain species (*Pinus contorta, Abies lasiocarpa, Populus tremuloides* and *Pinus flexilis*) exhibited very different stomatal and transpiration responses to seasonal increasing soil water deficits at a subalpine forest site in Wyoming. A decrease in maximum transpiration was evident for all species with increasing soil water deficits but *Abies lasiocarpa* showed a 50% decrease in transpiration regardless of air saturation deficit (D). Conversely, transpiration was greater on low versus high D days for *Pinus contorta* while *Populus tremuloides* showed less stomatal sensitivity to soil moisture than any other species.

Past research on plant water relations at FEF has focused on development of heat pulse techniques to measure whole tree water use (Swanson 1962) and the response of stomata to light, relative humidity and moisture stress (Kaufmann 1982; Kaufmann 1985a). Swanson calculated sap velocities for *Pinus contorta* and *Picea engelmannii* and derived some of the first transpiration rates for these species at FEF (Swanson 1967). Kaufmann produced some of the first modeled estimates of stand level water use at FEF (Kaufmann 1984; Kaufmann 1985b). His model suggests that in pure stands of the four species, consumptive water use ranks from highest to lowest for *Picea engelmannii, Abies lasiocarpa, Pinus contorta* and *Populus tremuloides,* respectively.

Current water relations research at FEF is focused on understanding the contribution of the three dominant species (*Pinus contorta, Abies lasiocarpa*, and *Picea engelmannii*) to mixed-species subalpine forest water use. Initial research on a forested and regenerating hillslope at FEF suggests that canopy conductance and its response to vapor pressure deficit is different for old and young trees (Figure 3). Future work will focus on quantifying and scaling species and age class differences in canopy conductance and water use as we assess the impacts of MPB infestation and management on site water balance for watersheds at FEF.

Rocky Mountain forests occupy some of the highest elevation sites in the US. At these sites, temperature exerts significant control on productivity, water use, species composition, and tree line. For example, Jobaggy and Jackson (2000) showed that temperature explained 78% of the global variation in tree line elevations. Differences in temperature during the summer months seem to control tree line elevation while temperatures during the winter months appear to control species composition.

Temperature may also exert considerable influence on tree water use. Research at FEF indicates freezing nighttime air temperatures limit leaf gas exchange the following day (Figure 4) for a range of age classes and species. The extent that freezing temperatures limit forest water use will depend on the duration and magnitude of these events in early spring and late fall. Because watersheds in the Rocky Mountain region typically span large elevation gradients, accurate scaling of vegetation water use to the watershed will likely need to account for air and soil temperature effects on canopy conductance and vegetation water use.

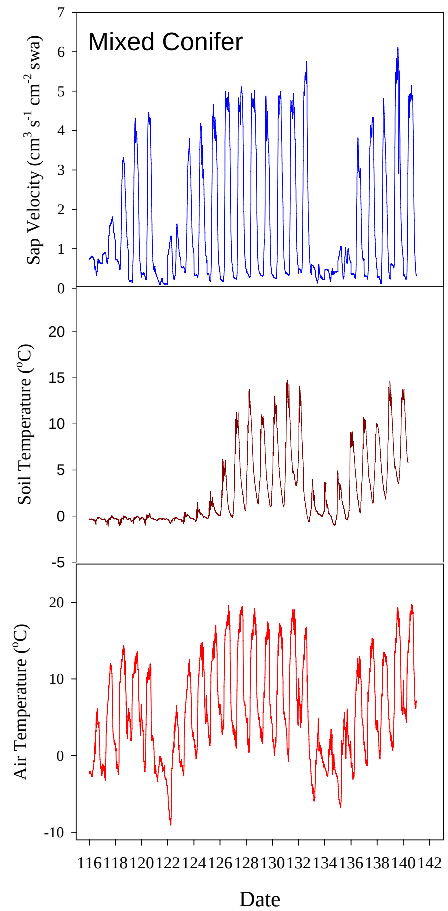

Figure 4. Effect of air and soil temperature on sap velocity in mixed conifer stands at FEF.

In addition to water availability and air saturation deficit, plant water status is dependent on the hydraulic architecture of the plant and the ratio of transpirational (e.g. leaves) and absorptive/transport (e.g. roots and sapwood) tissues. Consequently, in dryer environments, trees may allocate more resources to water uptake and transport tissues relative to leaf area and make physiologic adjustments in their hydraulic architecture. For example, *Pinus ponderosa* grows successfully along a range of xeric and mesic sites but exhibits distinct differences in hydraulic architecture and the ratio of leaves to absorptive and transport tissues. Callaway and others (1994) found *Pinus ponderosa* had higher ratios of leaf area to sapwood area in montane relative to desert environments and Maherali and DeLucia (2000) found increased xylem hydraulic conductivity in the same species growing in dry versus moist sites. Physiological adjustments are also likely important as trees grow larger and taller because increased height is accompanied by increased resistance to water flow. Recent research suggests that larger, older trees often allocate more resources to transport tissues relative to leaf area (Hubbard and others 2002; McDowell and others 2002). Increases in forest age and size have also been associated with increased sapwood permeability (Pothier and others 1989). Increased understanding of the physiological adjustments that trees make in response to changes in environment, age and size will be critical for better development of mechanistic models of how tree and forest water use will respond to disturbance and climate change.

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WATER QUALITY AND BIOGEOCHEMISTRY

Biogeochemical processes influence the water quality of headwater basins throughout the western US. There is growing concern that changing atmospheric inputs, most notably increased nitrogen deposition, have begun to alter watershed processes and threaten aquatic resources in high elevation basins (Fenn and others 2003; Galloway and others 2003). Rapid population growth in areas such as Colorado's Front Range has led to higher emissions from vehicle exhaust and coal-fired power generation and resulted in nitrogen loads that are 15 to 30 times above pre-industrial levels (Sievering and others 1996). During the past two decades, N inputs from precipitation have more than doubled at several high-elevation sites adjacent to Front Range population centers (NADP 2006; Figure 5). In some Rocky Mountain ecosystems, supply may exceed the capacity of plant, soil and microbial sinks to take up additional N and excess nitrogen may be exported from the system (Baron and others 1994; Fenn and others 1998; Burns 2003). In response to public concerns regarding increased N loading east of Colorado's continental divide, the director of Rocky Mountain National Park recently proposed a critical load (1.5 kg N / ha/yr) aimed at protecting the Park's terrestrial and aquatic ecosystems (Hartman 2006).

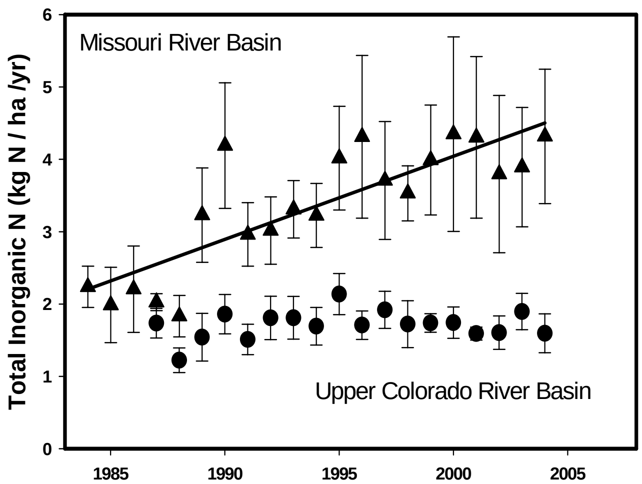

Figure 5. Annual nitrogen deposition in wetfall to high elevation sites (> 2500 m) east and west of Colorado's continental divide. Figure shows means and SE for 4 east and 2 west-side collection sites (NADP 2006).

Current ability to set critical loads for high-elevation ecosystems is limited not only by regional and local differences in atmospheric deposition (Figure 5), but also by uncertainties relating to internal N cycling and storage (Williams and others 1996). The biogeochemical processes that regulate nutrient export differ with elevation, aspect, watershed area, forest species composition and age, and edaphic and geologic attributes. Since soils represent the largest N sink in mountain ecosystems, the response of belowground processes to changes associated with land use practices, climate variability and landscape heterogeneity are critical to understanding the biogeochemical controls on water quality. For example, nitrate released in spring melt water is known to relate more closely to soil microbial activity (Brooks and others 1996) than to nitrate eluted from the snowpack. Like most terrestrial ecosystems, subalpine forests are limited by N supply (Fahey and others 1985) and they have the capacity to retain the bulk of N inputs (i.e. >90%; Stottlemyer and others 1997). Fertilization studies demonstrate that nutrients released from N-amended forest soils result from excess supply relative to plant and microbial demand (Binkley and Hogberg 1997; Perakis and others 2005) as well as from enhanced nitrate production (Fenn and others 2005). Further, critical load estimates for high-elevation watersheds must combine terrestrial nutrient uptake, transformation and storage processes with transfers between alpine and subalpine zones and terrestrial and aquatic ecosystems (Stottlemyer and others 1997; Seastedt and others 2004).

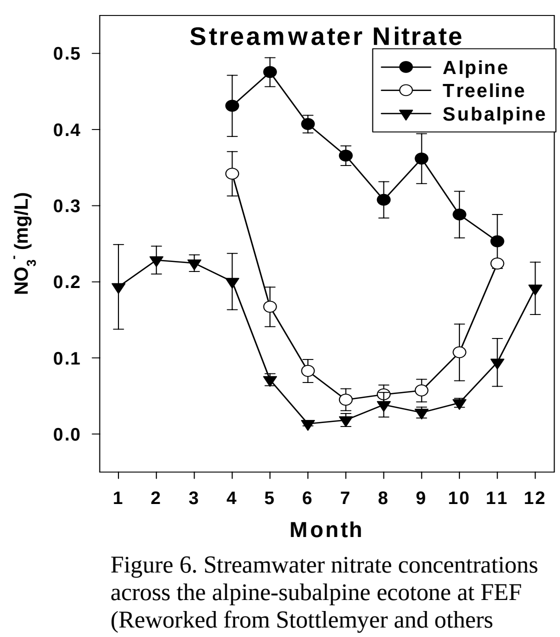

Figure 6. Streamwater nitrate concentrations across the alpine-subalpine ecotone at FEF (Reworked from Stottlemyer and others 1997 and FEF unpublished data).

Landscape Patterns in High-Elevation Biogeochemistry

Research at the Fraser Experimental Forest has advanced understanding of the links between terrestrial processes and streamwater chemistry in mixed alpine/subalpine basins (Stottlemyer and Troendle 1992; Stottlemyer and others 1997). Water draining the alpine portion of the Lexen watershed contains 2 to 10-fold more nitrate than the subalpine portion of basin (Figure 6). At treeline and within the subalpine forest, streamwater nitrate concentration is highest during the winter and early spring when biological demand is low, then declines to near detection levels during the summer growing season. Elevated nitrate in soil solution (not shown) contrasts to the declining streamwater nitrate concentration at snowmelt and indicates that biological N immobilization by subalpine plants and microbes efficiently retains inorganic N (> 90%) before it reaches the stream (Stottlemyer and others 1997). Low plant biomass and nutrient demand in alpine plant communities coupled with rapid leaching through coarse-textured alpine soils limit biological N retention and produce the more gradual decline in growing season streamwater nitrate.

The influences of snow cover and snow redistribution on the soil abiotic environment are key factors controlling nitrate export to surface waters in high elevation landscapes (Brooks et al 1999; Burns 2004). For example, seasonal freeze-thaw cycles that disrupt the rhizosphere environment have been shown to alter nitrification rates and release nitrate from roots, microbes and soil compartments (Groffman and others 1999). Temperature-regulated fluctuations in soil N processes are also evident at the watershed-scale where streamwater nitrate has been shown to track extreme cold periods (Mitchell and others 1996; Goodale and others 2003). In high-elevation catchments, the short growing season, weakly-developed soils and limited residence time of snowmelt within groundwater flow paths restrict retention of additional N inputs (Fenn and others 1998). Nutrient movement from alpine soils and export in stream water is coupled to snow melt, shallow subsurface lateral flow and stream discharge.

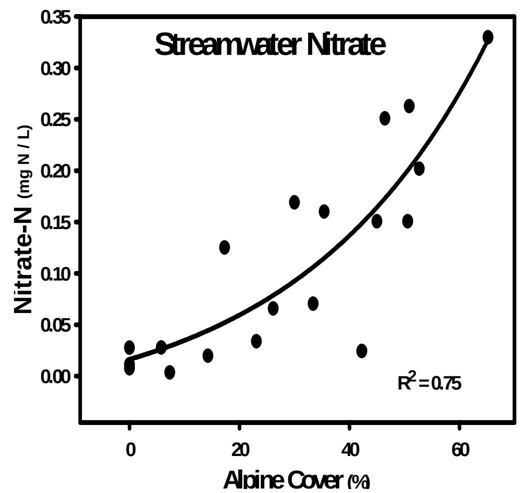

Figure 7. Streamwater nitrate in FEF catchments (Rhoades, unpublished data).

The strong relationship between streamwater inorganic N and alpine land cover (Figure 7), as measured in 18 catchments at FEF, demonstrates the relative importance of alpine biogeochemistry on watershed N export (Seastedt and others 2004). Still, it remains unclear to what extent landscape-scale variability in snow accumulation and soil development contribute to the overall pattern of watershed N export.

Legacy of Forest Harvesting

Research conducted at FEF has shown that removal of the subalpine forest canopy increases snow accumulation, shallow subsurface flow and nutrient export (Troendle and Reuss 1997; Reuss et al 1997). Fraser's paired watershed studies (Fool and Deadhorse Creeks) document augmented streamflow (Elder and others, in prep) and subsurface nitrogen export (Starr 2004) for at least 50 and 20 years, respectively, following clear cut harvests. A recent comparison of soil processes in regenerating clear cut and old growth stands in these basins indicates that nitrate production and release remain significantly altered 25 years after harvesting and may require a half century to recover from canopy removal (Rhoades and Hubbard 2005).

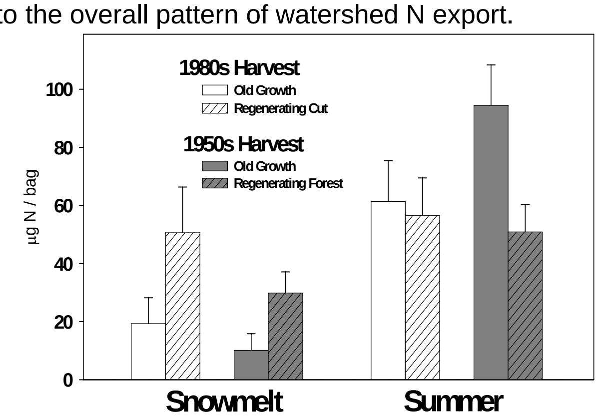

Figure 8. Soil nitrate in 25 and 50 yr old clear cuts at the FEF. Bars are seasonal means and SE for ion exchange resin bags placed in the upper 10 of mineral soil.

We found that in both 25- and 50 year-old harvest studies, snowmelt ion exchange resin (IER) nitrate was more than two times higher in harvested areas (Figure 8) and that nitrate represented a greater proportion of total IER-N (nitrate plus ammonium). In 25-year-old harvest areas, there was 1.7–fold more total IER-N released compared to adjacent uncut stands during spring snowmelt. We also measured 1.7 and 0.3 kg / ha more N mineralized and nitrified annually in the mineral soil of 25-year-old regenerating forest compared to uncut stands. Significant differences occurred during summer months when N turnover in harvested areas was twice that in adjacent old growth. N transformations did not differ between the 50-year-old stands and adjacent old growth forest. When combined with greater snow accumulation and subsurface flow in regenerating harvests, our findings indicate the potential for elevated watershed N export for half a century after subalpine forest harvest.

FLUVIAL GEOMORPHOLOGY AND SEDIMENT

A primary issue facing western water managers is increasing pressure on water resources from human population growth occurring over substantial portions of the western US. This pressure has caused state water users to look to National Forests to tap additional unappropriated waters and to establish only minimal instream flow protections for purposes of channel maintenance. Hence, maintaining water and aquatic resources on National Forest lands has become increasingly contentious. In the legal arena, the Forest Service has asserted a need for flows that are capable of transporting all of the sediment load delivered to stream channels in order to maintain channel conveyance capacity and streamside vegetation as an essential part of “securing favorable conditions of water flows” consistent with the Organic Act of 1897 (Gordon 1995). However, the agency has been largely unsuccessful in securing water for purposes of maintaining the channels on National Forest lands. This was due in part to inherent difficulties in defining the range of flows required to support the physical form and function of channel. Channel process and aquatic function are strongly tied to the physical structure of the channel, which, in turn, is controlled by topographic, geologic, and vegetative features and land management practices and natural disturbances specific to the watershed. Channel type is largely dependent on the overall patterns of sediment supply and runoff (snowmelt or rainfall-dominated), constrained within local geologic setting (slope and valley characteristics). Channels on western forests typically range from steeper step-pool structures in the upper portions of the watersheds to meandering pool-riffle forms in the flatter valley bottoms (e.g., Montgomery and Buffington 1997). Changes in either sediment supply or stream flow are likely to cause alterations in channel form and unwanted changes in aquatic resources, particularly in flatter, more alluvial segments (Ryan 1997). However, identifying change in channel form due to anthropogenic influences has proven difficult because of the scarcity of unaltered reaches that provide suitable reference conditions (Wohl 2001), or that the magnitude of the impact does not exceed the range of natural variability.

Flow alteration, associated typically with damming and diversion, has had an impact on the channel form and function of many stream systems in Rocky Mountain region. However, the effects of dams and diversions are largely dependent on the nature of the change in flow associated with the operation of the structures and the physical characteristics of the affected channel. For instance, the effects of flow depletion on channels downstream of large storage dams is well documented (e.g., Ligon 1995) and typical responses include decreased channel size, aggradation at tributary junctions, loss of sediment from the system, and encroachment of riparian vegetation. However, it is difficult to extrapolate the results of studies from large dams to low head diversions that are typically found on streams in National Forests. Much of the research on dams has been done on larger, low gradient channels that are more responsive to flow alteration. In these situations, the annual flow remains about the same though the hydrograph is more irregular, peak flows are reduced, and sediment is trapped behind dam. By comparison, streams on National Forest lands tend to be smaller, headwater streams which are presumably less morphologically responsive. Under a typical diversion scenario, the annual flow is reduced but peak flows are less impacted and sediment may be by-passed. As a result, changes in channel form downstream of diversion structures are often subtle or absent. For example, at St. Louis Creek on the Fraser Experimental Forest, where an estimated 40% of the annual streamflow had been diverted off-site for over 40 years, changes in form (smaller channel, vegetation encroachment) were relatively minor and limited to segments in unconfined valley bottoms where the systems is more alluvial in nature (Ryan 1997). The absence of widespread response was attributed in part to the fact that high flows (bankfull and greater), which are responsible for forming the physical channel structure, are still passed downstream on a relatively frequent basis (Figure 9). Hence, it was difficult to demonstrate that flow diversion had caused harm to the physical channel conduit at this and other sites in Colorado. However, with increased demands on water resources from National Forests, there is likely to be an increased call for water during peak flows. Hence, there is greater potential for physical changes in the channel structure at a site like St. Louis Creek – that is, a smaller channel due to sediment accumulation and vegetation encroachment is more likely when peak discharges are further reduced. Hypothetically, a smaller channel is no longer able to pass large flows when they do occur and, as a result, the channel may scour and "blow-out," resulting in a loss of channel function.

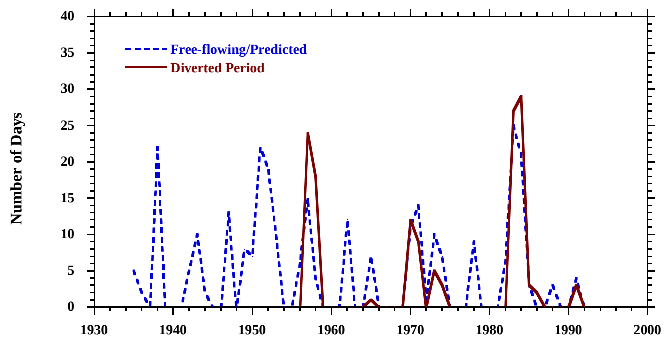

Figure 9. Difference in number of days for which greater than bankfull discharges were observed at St. Louis Creek after diversion began in 1956. In wetter years, the number of days was about the same as predicted had there been no diversion. Sustained bankfull discharges occurred every 1-2 years prior to flow diversion and about once every 5-7 years after diversion was initiated.

Sedimentation issues

Undisturbed forested areas in Colorado and Wyoming typically have low rates of erosion and sedimentation (i.e., Leaf 1970; Patric and others 1984), because much of the precipitation falls as snow, soil infiltration rates are relatively high, and rates of mass wasting are typically low. However, forest management activities have the potential to alter the nature of sediment delivery from hillslopes to channels, thus increasing the rate of sedimentation in channels. In particular, unpaved roads in forested environments present a major source of sediment affecting stream channels (Elliot 2000). Roads have lower infiltration rates and can generate increased runoff over bare surfaces – factors that can lead to increased flow and more sediment from altered hillslopes reaching channels. The effectiveness of Best Management Practices (BMP's) in reducing the impacts of forestry activities is an area of on-going investigation at the Fraser Experimental Forest and other areas of northern Colorado.

Increases in coarse sediment (typically moved as bedload) may have less influential effects on water quality issues, but a more pervasive effect on the physical structure of the channel. Rates of bedload movement in streams in Colorado and Wyoming are relatively low (Ryan and others 2005) and channels overall are largely stable in form in undisturbed watersheds. However, large disturbances, such as wildfire, can pose substantial threats to water quality and sedimentation in channels downstream from the disturbed areas. Following fire, peak discharges can increase by an order of magnitude or more on severely burned areas and erosion rates can increase by 2-3 orders of magnitude (Moody and Martin 2001). While higher runoff and erosion rates often decline to near background levels within 3-4 years, the impacts of sedimentation on aquatic resources and structures such as reservoirs may be more long-lasting and pervasive. The potential fire risk in the face of continuing drought and increased fuel loads due to insect-caused canopy mortality over much of the western US remains an on-going area of research.

Sediment concentration in streambeds can have a strong and pervasive effect on aquatic organisms. However, the linkages between watershed disturbances and effects on instream habitat and fish in natural settings are poorly understood. The question as to how much sediment is too much in streams remains unanswered. Moreover, increases in sediment supply must often be quite large in order to be detectable outside of the range of natural variability. For instance, at Fraser Experimental Forest, there was little detectable increase in export associated with additional sediment derived from forestry activities in the Fool Creek watershed study (Troendle 1983). Instead, measured increases in sediment yield were attributed to additional flow generated from the removal of timber rather than substantial increases in hillslope sediment production. Repeat surveys using historical archive data from channels downstream of former and planned harvest units are in progress at FEF to assess the influence of chronic and pulse disturbances on in-stream sedimentation and channel form.

In: Proceedings 2nd Interagency Conference on Research in the Watersheds. May 15-18 2006; Coweeta Hydrologic Lab., Otto, NC. pp 3-21.

RIPARIAN ECOSYSTEMS

Riparian areas occupy only 0.5 to 2.0% of the landscape in the western U.S., yet they are disproportionately important for maintenance of water quality and quantity (water storage and aquifer recharge), habitat for aquatic and terrestrial biota, sediment retention, stream bank building and maintenance, and provision of services of economic and social value, such as livestock grazing and recreation (Gregory and others 1991, Naiman and Decamps 1997, Naiman and others 2005). Because stream-riparian corridors are located at the lowest point within drainage basins, they can act as integrators of entire watersheds and may be particularly vulnerable to effects of land use conducted upslope and upstream. In the past, undesirable changes in riparian areas have resulted from unsustainable management or the failure to recognize linkages among streams, riparian areas, and uplands. Ongoing issues surrounding the management of riparian areas in the western U.S. include the impacts of forest harvest, livestock grazing, road construction, inadequate road maintenance, and recreation on the structure and function of riparian ecosystems (NCASI 2005). More recently, increasing interest has focused on the influence of natural disturbances such as wildland fire and insect outbreaks, altered hydrologic regimes (dams and diversions), and fuel reduction treatments on valued riparian characteristics and functions.

On National Forest lands, management of riparian areas can generally be defined as custodial (Gregory 1997), and frequently includes establishment of buffers and implementation of best management practices (BMPs) (Belt and others 1992, Gregory 1997, Mosley and others 1997). Although BMPs and the establishment of riparian buffers have mitigated the effects of forest harvest activities on stream water temperature and quality, current BMPs may not be effective in protecting all valued riparian functions, particularly in watersheds that have undergone extensive anthropogenic or natural disturbance, such as severe wildfire or insect infestation. In harvested watersheds, riparian buffers may be susceptible to blowdown; where fires have been suppressed, they may contain unnaturally high fuel loads (Dwire and Kauffman 2003). Another difficulty in the management of many riparian areas is the definition of reference or target conditions. Current attributes and condition of riparian areas reflect the historically recent (approximately 100-200 years) physical conditions of the landscape, as well as land management activities (NCASI 2005). Although the lingering effects of land management prior to the riparian protection may influence the structure, function, and composition of riparian areas for decades to centuries (Young and others 1994), historical legacies for most watersheds are largely unknown.
Attention to ecological context within drainage basin and the larger landscape is critical for effective management of riparian areas, as well as the connectivity between upslope and upstream management and condition of streams and riparian areas.

Despite several decades of focused research, riparian areas continue to be frontiers for the study of land/water interactions, ecosystem processes, impacts of watershed and landscape management, and the influence of natural disturbance on stream-riparian processes. The Fraser Experimental Forest (FEF) is well-positioned to contribute to the advancement of riparian research and improved management in the central Rocky Mountain region. Existing information on the management history, hydrologic and sediment regimes, and water chemistry for study basins within the FEF provide a strong baseline for examining the role of natural disturbance, such as large scale canopy mortality, and management activities, such as salvage logging, prescribed burning, and other fuel reduction treatments on subalpine riparian ecosystems. Stream-riparian corridors are dynamic, and the initiation of long-term studies allows for investigation of continuous change, including successional processes and responses to natural disturbance and management treatments. Past and ongoing research on stream-riparian ecosystems at FEF includes evaluation of BMP effectiveness, impacts of flow diversion on sediment transport, and riparian biota and processes, role of hillslope seeps and springs on streamwater, and effects of large-scale natural disturbance (insect-caused canopy mortality) on large wood dynamics and organic matter dynamics in headwater streams.

Diversion of water for municipal use and agricultural irrigation is common in many western watersheds administered by the USDA Forest Service. Although most of the diversions and dams in the western U.S. are built in mountainous areas, little is known about the influence of small dams and water withdrawals on aquatic and riparian biota and ecosystem processes along low order streams. As noted above, the influence of flow alteration on sediment transport and channel morphology depends on the timing of water diversion. Since most sediment moves during periods of high flow, stream channel condition may not be strongly impacted by water diversion occurring later in the season. .Studies have been initiated to examine the impacts of flow diversion on riparian and aquatic biota, and the role of hillslope and groundwater inputs on spatial recovery gradients. Concurrent work is being conducted in the Medicine Bow National Forest, Wyoming. Results will assist in determining the amount of water needed during different seasons to maintain riparian and aquatic biota, and contribute to proposed water management strategies.

Springs and seeps are common throughout the Rocky Mountains. In many glaciated watersheds, they are important sources of stream water, provide critical riparian and aquatic habitat, and can exert strong controls on streamwater chemistry. Hydrologic and chemical characteristics of springs may be influenced by forest harvest and other management activities, climate change, and natural disturbance. Ongoing research in the Fool Creek watershed, FEF, is addressing the influence of past forest harvest, elevation, and landscape position (aspect, distance from stream) on spring water temperature and chemistry in relation to stream water characteristics (Dwire and others 2006). This research compliments concurrent studies on slope and riparian wetlands to improve understanding of hydrologic connectivity within basins and drivers of surface and subsurface biogeochemistry. Current research efforts also provide a baseline for detecting changes in springs and streams due to insect-caused canopy mortality, planned fuel reduction treatments, and climate change.

In forested landscapes, riparian areas are important sources of large wood for streams and floodplains. However, riparian forest stands are frequently patchy, and variation from different sources can lead to spatial variability in large wood distribution that is often not recognized in management prescriptions for a given amount of large wood per unit length of stream (Young and others 2006). Chronic inputs of large wood to stream channels occur as a result of bank cutting, windthrow, and mortality of individual trees from adjacent riparian areas (McDade and others 1990, Bragg and Kershner 2004). Large pulses of wood may originate from near-channel sources following fire, windthrow, or insect infestations, or be transported from distant sites by debris torrents, avalanches, or landslides (Bilby and Bisson 1998, Bragg 2000, Benda and others 2003). At FEF, considerable stand-level data exists for basins that are currently being impacted by severe infestation of mountain pine beetle. Studies are underway that examine chronic and pulse inputs and sources of large wood — including source (upland, riparian) and process (avalanche, insect-caused, windthrow) — relative to upland and riparian stand structure. Results will provide increased understanding of the role of natural disturbance (avalanches and insect infestations) in the delivery of large wood to headwater streams, and contribute to the development of in-stream targets for large wood volumes in the Rocky Mountain region.

FISHERIES

Among the issues that influence water management in the western U.S. is the status of the aquatic biota, particularly fish. The tenuous condition of many populations of Pacific salmon is well known, but perhaps less recognized is that all of the species of salmonines in the interior West—the 14 subspecies of cutthroat trout, the Apache trout and Gila trout, golden trout, bull trout, and some forms of redband trout—have either been petitioned for federal listing under the Endangered Species Act, are currently listed as threatened or endangered, or are extinct (Young and Harig 2001). The majority of populations of these taxa are found in streams on federal lands, and the strongest populations tend to be found in streams draining basins afforded some additional protection, such as wilderness designation or status as a national park (Shepard and others 2005; Hirsch and others 2006). However, such designation is not sufficient to secure these populations; there are many examples of the extirpation of individual populations of these species in pristine habitats (Young 1995). This includes the Fraser Experimental Forest in Colorado, where indigenous Colorado River cutthroat trout have been lost from all streams in this area (Young and others 1996).

The threats facing these species are intimately linked to how water is managed in the West. As a consequence of water diversions for agricultural or municipal use, or of culverts that are impassable to upstream fish movement, many populations of these salmonids have been isolated in high-elevation stream segments that tend to be cold and unproductive. This isolation renders populations susceptible to environmental events, such as drought or fire-related debris torrents, that lead to local extinctions (Brown and others 2001; Morita and Yamamoto 2002) and prevent recolonization of these segments by mobile fish originating elsewhere in the basin. This has led to studies of how habitat quality and quantity affect population size, particularly of Colorado River cutthroat trout and greenback cutthroat trout in the Central Rocky Mountains (Young and others 2005). Ironically, these isolated segments also represent some of the best refuges for native salmonids, because barriers at their downstream ends prevent the invasion of nonnative species, such as brook, brown, or rainbow trout, that would otherwise replace or hybridize with the native taxa (Dunham and others 2002). Recognizing this dilemma and examining the consequences of habitat isolation or nonnative fish invasion are of critical importance to fish managers throughout the inland West (Fausch and others, in press).

The role of fire in altering fish habitat, population persistence, and nonnative fish invasion is also of great concern. Even today, the effect of fire on stream fish populations remains poorly understood, but isolated studies from different parts of the West are beginning to fill this gap. Occasionally, high-severity fires generate sufficient heat to lead to immediate fish kills (Rinne 1996), but more common are post-fire debris torrents and blackwater events resulting from summer thunderstorms that eliminate fish populations (Bozek and Young 1994; Brown and others 2001). Historically, such populations would have been immediately refounded by migrating fish that survived in local refugia or avoided these events by occupying other portions of a watershed, but as noted above, human-built barriers often make this impossible (Rieman and others 2003). A related concern is that habitat changes resulting from fire—increased water temperatures, greater sediment loads, and reduced channel stability—are often associated with conditions favoring nonnative trout. However, because western trout species evolved with such disturbances, they may be more resilient than nonnative species introduced from areas where fire-related habitat changes are uncommon (Dunham and others 2003). Preliminary results from some Montana basins suggest that native cutthroat trout recover more rapidly after fire than do introduced brook trout (Sestrich 2005).

Many questions remain to be answered with regard to native fish species and water management in the Rocky Mountain West. Continued research on fish response to forest disturbances such as fire, large-scale insect-related tree mortality, and drought is a priority. Also, formal systematic conservation plans (Margules and Pressey 2000) for restoration of rare fish in the West have rarely been developed, and it may be possible to construct such a plan for the stream network on the Fraser Experimental Forest. Similarly, existing diversions in this area may present opportunities to measure the ability of nonnative fish to move through structures, with the objective of engineering more effective barriers to nonnative fish passage.

A NATURAL DISTURBANCE RESEARCH OPPORTUNITY

Populations of mountain pine bark beetle (MPB) and other forest insects have increased rapidly in western North America during the past decade. The impacts of MPB-induced mortality on watershed processes and aquatic resource conditions in Rocky Mountain forest ecosystems are poorly understood. Widespread MPB-related forest mortality has created public anxiety over human safety and property loss, associated with perceptions of heightened wildfire risk. Such concern led to enactment of the Healthy Forest Restoration Act of 2003, legislation that gives federal land managers the administrative tools to address hazardous fuel loads and other forest health issues rapidly. Unfortunately, federal resource managers working in much of the Rocky Mountain West currently lack adequate information to evaluate the influence of fuel reduction treatments on forest productivity, water quality, streamflow and other watershed resources.

FEF is located near the epicenter of a large MPB outbreak that is affecting lodgepole pine in subalpine forests of central Colorado. Significant MPB-related lodgepole pine mortality was first observed at FEF in 2003; by 2005 most mature pine stands had become infested. This outbreak places FEF in a unique position to address critical gaps in the understanding of the watershed consequences and management responses to the outbreak. FEF researchers are focusing on two fundamental questions regarding the effects of bark beetles on subalpine forest watersheds:

1) How does the present bark beetle outbreak influence watershed processes and forest conditions in managed and unmanaged basins?
2) What are the consequences of forest management manipulations associated with the insect outbreaks and other forest health management activities?

To evaluate biogeochemical and hydrologic changes we will utilize more than fifty years of snowpack and streamflow measurements and two decades of precipitation and streamwater chemistry. Our assessment of management activities will:

1) quantify the influence of salvage operations on nutrient, carbon, sediment and large wood retention within riparian buffers and validate the effectiveness of watershed best management practices for protecting water quality and aquatic resources;
2) evaluate how mechanical fuel reduction treatments (chipping and mastication) and post-harvest site preparation impact tree seedling establishment and growth, plant nutrient and moisture relations, and biogeochemical and hydrologic processes;
3) assess the impacts of forest road construction and retirement on hillslope hydrology and nutrient and sediment fluxes.

Greater understanding of these management practices will assist national forest managers protect and sustain upland, riparian and aquatic resources.

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