Chapter 11: Ecoregion 7.1.8 Coast Range: Caspar Creek Experimental Watersheds, California

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Introduction

This chapter is a review and synthesis of research conducted at the Caspar Creek Experimental Watersheds (CCEW) on stream nutrients and their responses to forest management. Results from relevant scientific studies conducted at CCEW are provided, as well as a description of future potential research. This information is relevant to water quality regulatory agencies.

Site Description

CCEW are located at lat. 39° 21′ N, long. 123° 44′ W (fig. 11.1), between 5 and 10 km from the Pacific Ocean on the western slope of the northern California Coast Ranges, in the western portion of Jackson Demonstration State Forest. The land within the experimental watersheds is owned by the state of California and is administered by California Department of Forestry and Fire Protection (CAL FIRE). The 473-ha North Fork and 424-ha South Fork watersheds span an elevation of 30 to 322 m. Both watersheds are underlain by shales and sandstones of the Coastal Belt of the Franciscan Complex, which have developed sandy to gravelly loam soils, often with clay to clay-loam subsoils. The main stem channels are gravel bedded and have incised slightly into narrow former floodplains. Tributary channel profiles are broken by frequent headcuts.

Climate is moderate at the site, with a mean December minimum temperature of 4.9 °C and a mean July maximum of 21.4 °C. Mean annual rainfall is nearly 1200 mm, ranging from 400 to 2202 mm over the 54-year monitoring period. Snow is hydrologically insignificant. Rainfall is strongly seasonal, with 95 percent occurring in October through May, and tributaries draining areas <20 ha are generally dry by June. Summer fog is common. Fog drip can account for as much as 3 percent of annual rainfall on exposed ridgetops, but drip rates are considerably lower elsewhere in the watersheds (Keppeler 2007).

The original old-growth forest, dominated by coast redwood (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), was clearcut between about 1860 and 1904. By 1961, the second-growth forest, composed of the same species, averaged 85 years old in the South Fork and about 20 years younger in the North Fork. Timber production has been the primary land use at the site.

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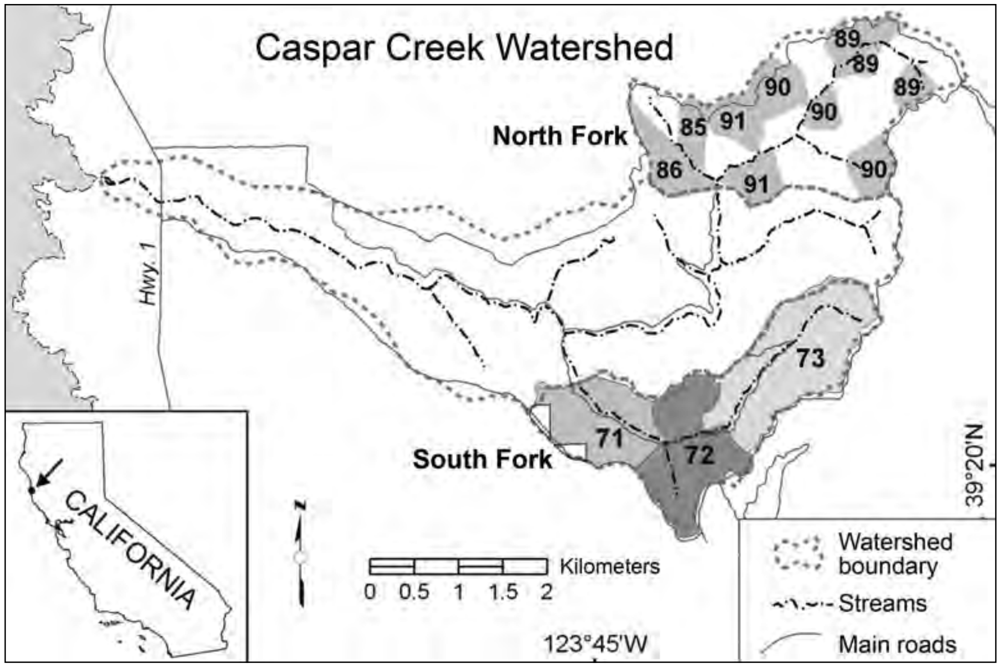

Figure 11.1—North Fork and South Fork Caspar Creek Experimental Watersheds. Numbers indicate the years that shaded areas were logged for the second time. Old-growth forests were first logged from approximately 1860 to 1904. This coastal watershed discharges into the Pacific Ocean.

Research History

In 1961, the U.S. Forest Service (USFS) Pacific Southwest Research Station and CAL FIRE entered into a cooperative agreement to study the effects of logging on water quality, flooding, and salmonid resources at Caspar Creek. The initial CCEW watershed experiment employed the North Fork as a reference watershed to study the effects of road construction in 1967 and tractor-yarded selection logging during 1971–1973 in the South Fork, with effects on streams monitored at basin-mouth weirs. Timber operations were carried out using practices characteristic of the period immediately preceding institution of modern forest practice regulations in California.

The second CCEW watershed experiment was designed to evaluate cumulative watershed impacts and was carried out in accordance with forest practice rules in use at the time. Gaging began in late 1985 at 13 nested gaging stations in the North Fork watershed. Three North Fork tributaries were selected as unmanaged, reference watersheds, and 37 percent of the watershed was clearcut logged and yarded, primarily by skyline cable, between 1989 and 1992. Logging debris was broadcast burned on 19.5 percent of the watershed area in 1990–1991.

A third major set of logging treatments, called CCEW Experiment Three (USDA FS 2016c), is now being implemented in the South Fork. This study is evaluating effects of reducing stand density from zero to 75 percent in eight subwatersheds on sediment yields and their sources, peak flows, water movement from hillslopes to channels, low flows, water temperature, macroinvertebrates, subsurface moisture dynamics, and stream nitrogen (N), phosphorus (P) and a wide array of other nutrients. Prelogging monitoring of total nutrient loads of four study subwatersheds has been completed (Dahlke et al. 2018), and export of dissolved N and P has been measured for 10 storm events between October 2016 and May 2017. Timber harvesting in the South Fork began in June 2017.

Availability of publications and data—
Many of the datasets collected for the watersheds (table 11.1) are available on the CCEW website (USDA FS 2016a), or from Pacific Southwest Research Station or CAL FIRE by request. Daily streamflow and meteorology may be downloaded in formats that permit comparisons with other experimental forest and ranges (EFRs) and long-term ecological research (LTER) sites at the ClimDB/HydoDB website (LTER Network 2013). Ziemer (1998b) summarized methods and results for the experiments, and CAL FIRE (2005) described the natural and human setting in the area. Cafferata and Reid (2013) reviewed CCEW results and described how the information has been applied by regulatory agencies. Morken and Ziemer (1998) and Reid (n.d.) provided annotated bibliographies of CCEW publications. Most publications are available on the CCEW website (USDA FS 2016b) or on those of cooperating agencies.

Biological Responses to Stream Nutrients N and P

Issues of Concern

Beneficial water uses of high concern in the region include threatened and endangered species, especially anadromous salmonids, domestic water supply, freshwater habitat, and water contact recreation. The North Coast Regional Water Quality Control Board found that most waters draining primarily forested watersheds in this region have only temperature and sediment impairments (NCRWQCB 2014), and none are listed for nutrient loads related to silviculture. Nutrient loads impair six waterbodies, all of which drain significant urban or agricultural areas.

Although forest lands are not identified as a source of excess nutrient loads in the region, forestry activities can affect downstream loads by altering streamflow, sediment, riparian forest composition, and stream temperature, which, in turn, affect nutrient transport. Where forest lands are located in watersheds with agriculture or urban areas, runoff from forests dilutes nutrient inputs from those areas. In such settings, increased nutrient output from forests, or conversion of forest land to other uses, might contribute to a cumulative downstream nutrient impact by reducing the effectiveness of dilution, even if nutrient outputs from the forested or converted watershed remain below prescribed limits.

Maintenance of productive forests is a high priority in the region because of their economic importance. Currently, fertilizers are rarely used on the region's forests, but cumulative nutrient depletion could prompt increased application, leading to increased stream nutrient loads. If fertilizers are not applied and N fixers such as those associated with *Ceanothus* spp. are suppressed with herbicides to reduce competition for young conifers, depletion could modify long-term site productivity and also affect nutrient loads. Past riparian logging has altered

Table 11.1—Principal datasets collected at Caspar Creek

Category	Attribute	Comments
Climate	Solar radiation	1965–1968, 1988–present, various periods and sites
	Air temperature	1967–1968; 1989–present, various periods and sites
	Humidity	2001–present, various periods and sites
	Windspeed	1998–2001, 2009–present
Hydrology	Rainfall	1961–present, various periods and sites, two continuous
	Fog drip	1998–2001; 2012–present, multiple sites and methods
	Throughfall	1998–2001, two sites, 2006–2010, two sites
	Stemflow	1999–2001, 24 trees
	Soil pipeflow	Various periods, 1986–present, four sites
	Streamflow	1962–present, 25 sites various periods, weirs (NF and SF)
Water quality	Chemical constituents	1968–1969, 1991–1996, 2003–2005, 2016–present, various components
	Dissolved oxygen	1968–1969; monthly 1989–1990, four measurements
	pH and conductivity	1968–1969, monthly 1989–1990, NF 1991–1996, four measurements
	Stream temperature	1963–1969, 1988–present (NF), 1998–present (SF), various periods at 11 sites
	Turbidity	Occasional before 1996; continuous at multiple stations since then
	Nutrients	1991–1996, 13 sites (NF); 2016–present, 5 sites, (SF)
Soils	Hydraulic conductivity	Multiple sites
	Piezometric pressure	1987–present, four sites, various periods
	Soil moisture	1987–present, four sites, various periods
	Soil temperature	2011–present, two depths
Erosion	Landslides	1986–present (NF), 2001–present (SF), Annual stream maps
	Plot inventories	1975 SF, 1996 NF
	Road surface erosion	2005–2007, measurements at culverts; 2018–2019
	Headcuts and gullies	2000–present, occasional remapping
	Pipe erosion	1989–1993, pump samples during storms, coarse in wire baskets

Table 11.1—Principal datasets collected at Caspar Creek (continued)

Category	Attribute	Comments
Stream sediment	Concentration	1962–present at each gage; pump samples and depth integrated
	Suspended sediment load	1962–present, various periods at 27 stations
	Bedload	1978–1980 manual samples; 1987–1997 pit sampler; one site
	Organic load	2002–2003
	Sedimentation	1962–present, annual bathymetric survey of weir ponds
	Sediment grain sizes	1986–1993 pebble counts; 1987–1997 pit samples; 1967–1969 McNeil samples
	V-star (pool infill)	1991–present, measured annually until 2012, then every 2 years
Channel condition	Woody debris	1986, 1994, 1996; since 1998 tagged logs mapped every 2 years
	Cross sections	1979–present (NF), 2000–present (SF), every 2 years
Aquatic biota	Redd surveys	1990–1992; 2000–present
	Downstream migrants	1964, 1968, (NF and SF); 1986–1988, 2000–present
	Upstream migrants	1963–1964 (NF and SF), 2000–present
	Rearing salmonids	1967–1969, 1986–1995 (NF and SF), 2000–present
	Salamander biomass	1986–1995, Pacific giant salamanders; electrofishing
	Macroinvertebrates	1965–1969, 1987–1994, 2002–2003, 2016–present
	Leaf decay	1988–1993, leaf packs; autumn measurements; three sites, (NF)
	Algae growth	1987–1994, tiles; 15 sampling dates, 5 sites, (NF)
Terrestrial biota	Growth and yield	1958–present continuous forest inventory plots measured every 5 years
	Nutrient content	2012–2013, element concentrations in conifers; two sites
	Seral development	1982–1983, 1990–1993; plots with a gradient of clearcut ages
	Riparian treefall	1998–present, every 2 years

NF = North Fork, SF = South Fork.

instream productivity, and recent reductions in anadromous fish runs contribute to altered nutrient cycling in riparian zones by reducing marine nutrient inputs from returning salmonids. Conversion of forest lands to urban development and agriculture, primarily vineyards, can lead to significantly increased nutrient loads. Cannabis (*Cannabis sativa* or *C. indica* (Lam.) E. Small & Cronquist) cultivation, a multibillion dollar industry, affects forest land in the area by degrading water quality through use of fertilizers and pesticides (Bauer et al. 2015, Butsic and Brenner 2016, NCRWQCB 2013). Water contact recreational uses in the region are affected by toxic blue-green algae blooms, which are promoted by high temperatures, low flows, and high nutrient loads.

Findings From Studies

Overall N and P conditions—

Measurements of instream nitrate (NO_3^-) under forested conditions at CCEW (Bottorff and Knight 1996, Dahlgren 1998a, Kopperdahl et al. 1971) show concentrations generally lower than the median value reported for forested streams elsewhere in the United States (Binkley et al. 2004). Streamwater in CCEW reference watersheds usually had NO_3^- concentrations less than the detection limit (0.02 mg/L as NO_3^-) and had a maximum observed concentration of 0.7 mg/L (as NO_3^-) during storms. The USEPA (2000) reference condition value for ecoregion 1 (Coast Ranges) is 0.09 mg/L, and the level for eutrophication concern is 1.3 mg/L (Roche et al. 2013). Dahlgren (1998a) evaluated N pools in biomass and soils in a North Fork reference watershed and measured NO_3^- concentrations in streamflow, rainfall, throughfall, soil solution, and pipeflow, which is bulk transport through naturally occurring conduits in the soil called soil pipes. Annual flux in streamflow from the watershed averaged 0.025 kg N/ha for the 5-year period.

Similar analyses for P were performed and foliage was found to enrich P concentrations in throughfall. Annual P flux in streamflow averaged less than 0.0014 kg/ha, and orthophosphate (PO_4^{3-}) concentrations ranged between undetectable and 0.1 mg/L. Measurements of PO_4^{3-} concentrations in streamflow were similar to those reported by Binkley et al. (2004) for other western conifer forests. Natural undisturbed forest background stream water concentrations for PO_4^{3-} usually range from 0.005 to 0.05 mg/L (Dunne and Leopold 1978), and the level for eutrophication concern is 0.15 mg/L as PO_4 (Roche et al. 2013).

Riparian zones in the area receive annual inputs of marine-derived P and other nutrients through inmigration of adult anadromous salmonids. Moore et al. (2011) found that recent reductions in salmonid populations have reduced P imports to the region's streams to the point that the annual flux may be shifting to net export by outmigrating immature salmonids.

Effects of N and P: organismal responses—

Many CCEW studies have focused on salmonids and other aquatic biota (table 11.1). Reports from early CCEW experiments documented salmonid conditions in the North and South Forks (Graves and Burns 1970, Kabel and German 1967). Hess (1969) measured the rate of insect infall from the riparian zone at stations along the South Fork in 1966 and 1968 and summarized benthic macroinvertebrate samples from the North and South Forks. Burns (1971) found no relation between P measurements and salmonid biomass at Caspar Creek and several other streams and concluded that other habitat influences were more important.

Although biological results during the North Fork experiment were not analyzed directly with respect to nutrient levels, they may be used to characterize biological conditions under the nutrient cycling regime present in the 1990s. Nakamoto (1998) found large variations in juvenile coho salmon (*Oncorhynchus kisutch* Walbaum) and steelhead trout (*O. mykiss* Walbaum) biomass during the period in which nutrients were monitored. Harvey and Nakamoto (1996, 1997) experimentally manipulated juvenile populations within enclosures in both the North and South Forks to examine interactions between these two species. Monitoring of larval Pacific giant salamander (*Dicamptodon tenebrosus*) showed increasing numbers between 1991 and 1996 in the North Fork, but no clear trend in the South Fork (Nakamoto 1998).

Bottorff and Knight (1996) identified benthic macroinvertebrates colonizing rock packs emplaced along the North Fork between 1987 and 1994. Downstream stations had significantly higher densities of macroinvertebrates and more taxa present than upstream stations. The study also found rapid instream alder leaf decomposition rates in emplaced leaf packs, and, in one case, the measured decay rate (k) of 0.0912/day exceeded the highest published rate. Bottorff and Knight (1996) also measured chlorophyll *a* (chl *a*), assessed algal biomass, and identified and counted diatoms on emplaced clay tiles. Chl *a* levels and algal biomass were significantly higher in fall and increased downstream.

Additional instream biological work was carried out after nutrient monitoring ended. Gallagher et al. (2010, 2013) described results of intensive monitoring of various life stages of anadromous salmonids in the Caspar Creek watershed, which documented a decline in coho salmon populations. This trend was not as evident in 1993–2003, when Valentine et al. (2007) found that populations of juvenile salmonids in the South Fork were within the range reported by Burns (1971) for 1967–1969.

To study the effects of particulate organic sediments, Wilzbach et al. (2009) evaluated algal chl *a* in the suspended load, benthic and drift macroinvertebrates, salmonids, and microbial respiration in the North and South Forks during six periods in 2002–2003. Overall, suspended organic particles influenced instream attributes in ways similar to nonorganic components of the sediment load.

Control of nutrient dynamics by stream and watershed processes—Dahlgren (1998a, 1998b) found that NO_3^- concentrations increased with increasing streamflow during storms, suggesting that the source of NO_3^--bearing inflow differs for stormflow and baseflow. Stormflow is likely to be supported more by shallow subsurface flow through the NO_3^--rich A and AB horizons, while baseflow originates from deeper zones (O’Geen et al. 2010, Swarowsky et al. 2012). Sedimentary rocks in CCEW contain significant N, so some of the NO_3^- in streamflow may originate from bedrock weathering (Morford 2015).

Studies of Other Factors Relevant to Stream Nutrients N and P

Many physical and biological conditions that can affect nutrient cycling in forested watersheds have been evaluated at CCEW (table 11.1). Henry (1998) described many of the monitoring methods used. Rainfall monitoring began in the watersheds in 1961, and other climatic data collected at various times include windspeed, solar radiation, relative humidity, throughfall, fog drip, and air temperature. Fog drip was found to contribute little moisture over most of the watershed (Keppeler 2007), and data showed a loss of 22 percent of rainfall to evaporation of foliar interception in second-growth stands (Reid and Lewis 2009). Subsurface hydrology has been monitored in a second-growth watershed, a clearcut watershed, and along a slope transect across a logging road (Keppeler and Brown 1998). Monitoring demonstrated the importance of soil pipes as a source of stormflow (Albright 1992).

Streamflow monitoring has been a fundamental aspect of the CCEW studies since the project began in 1961. Thirteen additional gaging stations were installed in the North Fork in 1985, and 10 more in the South Fork in 2000. Keppeler (1998) described water yield results and evaluated dry-season flows using records from the weirs and from instream wells installed near tributary gaging stations. After timber harvesting, increased water yields and summer flows were documented at the weirs for both the North and South Forks of Caspar Creek.

Sediment is a second major focus of CCEW research (Lewis 1998). Sediment load estimates were originally based on sediment rating curves, but the Turbidity Threshold Sampling protocol was developed for the watersheds in 1995 (Lewis and Eads 2009), and loads for subwatersheds are now estimated using calibrated 10-minute turbidity readings. Bedload sediment is trapped in the weir ponds, and infill has been measured annually since 1962 using bathymetric surveys. Bedload was also measured from 1987 to 1997 in pit traps immediately upstream of the North Fork weir pond, and grain-size distributions of the transported material were measured.

Madej (2005) found that particulate organic matter (POM) accounted for ~19 to 24 percent of the annual suspended sediment load in the North and South Fork watersheds during 2002–2003, with the relative importance of POM decreasing with increasing discharge. Dahlgren (1998a) reported similar findings in the North Fork for the period 1991 to 1996.

Kopperdahl et al. (1971) reported concentrations of 83 to 155 ppm for total dissolved solids in the North Fork in 1968–1969, with concentrations that decreased with increased flow. Dahlgren (1998a) listed molar concentrations of the chemical constituents in streamflow measured between 1991 and 1996, and calculated total dissolved loads and the percentage of dissolved organic matter. Sanderman (2007) measured dissolved organic carbon (DOC) in soil solutions, pipeflow, and stream water in a reference watershed during 2003–2005 and found that the pipeflow strongly influenced the characteristics of DOC in streamflow.

Many CCEW studies have focused on erosion processes. Major sources of sediment input include channel erosion (Reid et al. 2010), and landslides with volumes greater than 200 m^3 (Reid and Keppeler 2012). Annually mapped streamside landslides are a lesser source. Plot erosion measurements showed minimal surface erosion in forested subwatersheds where much of the sediment is redeposited on hillslopes (Rice 1996). Ziemer (1992) found that sediment loads in soil pipes in a forested watershed were low.

Caspar Creek channels are strongly influenced by woody debris. Wood loading was measured in the North Fork in 1980 and 1986, and in both forks in 1994 and 1996. Wood was mapped and measured along the North and South Forks in 1998, and tagged pieces and new inputs have been remapped every 2 years since then (Hilton 2012). Russell (2009) described the species composition in riparian plots along the North and South Forks in 2001, and Reid and Hilton (1998) assessed blowdown in plots along the North Fork after a pair of major windstorms.

Information on stand characteristics is available from CAL FIRE. Continuous Forest Inventory plots have remeasured woody vegetation every 5 years since 1959, and Woodward (1986) and Rivas-Ederer (1998) inventoried both herbaceous and woody vegetation in plots across a gradient of disturbance ages.

Summer stream temperatures were monitored in the North and South Forks from 1963 to 1969, and monitoring resumed in the North Fork in 1988 and in the South Fork in 1998 (table 11.1). Under forested conditions, maximum dry-season stream temperature was 16.7 ^{o}C and seldom exceeded 15.6 ^{o}C, which was within an acceptable range for salmonid rearing. Nelson et al. (2007) found that air temperatures along a South Fork transect through the riparian zone increased upslope, with mean maximum weekly temperatures 4 to 5 °C higher at the upland sites than at the main-stem South Fork. Light levels were also measured at sites along the North and South Fork channels in 1965 to 1968, and again between 1989 and 1991 on the North Fork.

Dose-Response Studies

Dose-response studies for stream nutrients have not been conducted at CCEW.

Reference Watersheds

Three North Fork subwatersheds, ranging from 16 to 39 ha, serve as permanent references that are often referred to as "controls" in reports of CCEW research. Onsite human disturbance in the references is minimal, although residual effects of old-growth logging, 120 to 135 years ago, are reflected in the current characteristics of these second-growth stands, such as the presence of abandoned skid trails, and the incised stream channels. Although these references serve well for hydrologic and sediment research at the scale of the North and South Fork watersheds, they are not useful for studies of physical and biological conditions along the larger main-stem North and South Fork channels; such studies have usually used North Fork reaches adjacent to second-growth forest as reference reaches.

A reference subwatershed at the North Fork headwaters (Munn, abbreviated as MUN) has hosted multiple studies, in part because of the long-term subsurface hydrological monitoring carried out there. Soil moisture, pore pressure, and pipe-flow have been measured during various periods since 1987, and the site served as a primary source of reference data for a study of nutrient cycling (Dahlgren 1998a, 1998b) and for recent studies of N dynamics (Lennon and Houlton 2014, Mnich and Houlton 2016).

The reference watersheds are undergoing long-term changes as the second-growth forest matures, and future forest conditions will probably differ from those in the original old-growth stands. Wildfire recurred at 6- to 20-year intervals in the area before Euro-American settlement (Brown and Baxter 2003) and generated little tree mortality in the stands. Modern fire suppression has removed underburns from the ecosystem, and understory vegetation will change in response. In addition, two pathogens are becoming established in the region. Black-stain root disease (*Leptographium wagneri*) was identified for the first time at Jackson Demonstration State Forest in 1971, and recent high mortality rates for Douglas-fir and true fir, possibly associated with the pathogen, suggest that these tree species will become less common as the reference forest ages. Sudden Oak Death (*Phytophthora ramorum*) has also been found in Jackson Demonstration State Forest, and this disease may reduce tanoak (*Notholithocarpus densiflorus* (Hook. & Arn.) P.S. Manos, C.H. Cannon, & S.H. Oh) in the watersheds. In addition, future hydrologic regimes and forest characteristics in the area are likely to change in response to climate change.

Downstream characteristics may also shift through time. Recent woody debris is much smaller than relict old-growth wood and thus will decay and be displaced more quickly and will affect channel processes differently. In addition, declining populations of anadromous fish are reducing the inputs of marine-derived nutrients to streams and riparian zones (Moore et al. 2011).

Reference watersheds for the CCEW Experiment Three in the South Fork were selectively logged from 1971 to 1973, before implementation of modern forest practice rules, and contain networks of tractor skid trails and spur roads. These watersheds provide reference conditions for the forest that would be present after 1960s and 1970s logging if no further activities took place, and so are appropriate for evaluating the incremental effect of third-cycle logging taking place in the South Fork.

Cross-Site and Regional Studies

Nearly a third of the more than 225 publications, theses, and technical reports on CCEW research have focused on cross-site comparisons. CCEW results are often included in tabulations of sediment yields from forested and logged watersheds and in reviews of the hydrologic effects of logging. CCEW data are also often used to develop models or to test model results. For example, long-term data from CCEW were used by Breña Naranjo et al. (2011) to test a method for estimating evapotranspiration as forests regrow, and by Wang et al. (2010) to test flow routing models for watershed-scale applications of the Water Erosion Prediction Project model.

Other studies used CCEW data to represent conditions in temperate rain-dominated forests for comparisons over a range of climatic conditions. For example, Grant et al. (2008) drew upon these data in an evaluation of the effects of logging on peak flows, and Jones and Post (2004) for a comparison of hydrologic responses to tree harvesting in coniferous and hardwood forests. CCEW data were used by Jones et al. (2012) in an analysis of climate- and land use-related streamflow changes at 35 North American watersheds, and by Ponce-Campos et al. (2013) to evaluate the relation between water use efficiency and water availability among 29 sites in the United States and Australia. CCEW participates in ongoing research examining rates of wood decomposition as part of a continentwide study at 50 USFS and U.S. Department of Agricultural Research Service sites in the federal Ecotrends network (Peters et al. 2013). CCEW is among 18 USFS sites with climate monitoring stations that meet the International Co-operative Programme (ICP) Level II standards established by the ICP on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests 2010).

Much CCEW research has been carried out as an integral part of cross-site studies. An early sequence of papers examined biological (Burns 1971), physical (Burns 1970, 1972), and chemical (Kopperdahl et al. 1971) effects of road construction and logging across several coastal watersheds, including both forks of Caspar Creek. Other studies have compared DOC processing in forested CCEW soils with that in grassland soils (Sanderman and Amundson 2008); POM loads in managed and old-growth redwood watersheds (Wilzbach et al. 2009); bed-material sizes and pool sedimentation across a range of sediment input rates (Lisle 1995, Lisle and Hilton 1999); and controls on N cycling and denitrification rates using N isotopes across a range of California ecosystems (Mnich and Houlton 2016).

CCEW was selected as a site for intensive monitoring of anadromous salmonids to aid design of a monitoring strategy for use throughout coastal California (Gallagher et al. 2010). Data from CCEW and several other intensively monitored watersheds are used to permit interpretation of sparser data collected at other coastal watersheds (Adams et al. 2011). Moore et al. (2011) combined data from CCEW and other monitoring sites to estimate rates of import and export of marine-derived P by anadromous fish.

Responses to Management and Natural Disturbances

Much CCEW research has focused on the effects of timber harvest operations on watershed processes and stream channel characteristics. Cafferata and Reid (2013) summarized CCEW results relevant to assessing management influences and described the ways that these results have been applied.

Kopperdahl et al. (1971) did not detect significant differences between nutrient concentrations in the North and South Forks after 1967 road construction. They noted that the major water quality effects were increased carbon dioxide (CO_2) and reduced dissolved oxygen (DO) from decay of instream logging debris and increased temperature from reduced shade. Management effects on nutrients were studied in more detail during the second harvesting treatment. Dahlgren (1998b) measured N content across the array of ecosystem components in reference and clearcut watersheds between 1991 and 1996. Losses attenuated quickly as a result of uptake by rapidly growing redwood stump sprouts. However, enough N was exported in the extracted logs that a deficit might occur after multiple logging cycles without adequate N fixation by blue blossom (*Ceanothus thyrsiflorus* Eschsch.), a shrub often controlled with herbicides. Moderate NO_3^- concentrations in stream water from clearcut watersheds decreased rapidly downstream and with time after logging, so little effect is expected farther downstream or with increasing time. Over a hypothetical 80-year clearcut rotation, the greatest logging-related change in N was from removal of logs, with lesser export in eroded sediment and leaching into streams.

Dahlgren (1998a) found that soil solution NO_3^- increased after logging, probably because of increased mineralization in warmer and moister soils and reduced uptake by vegetation. Nitrate concentrations in streams the first years after logging ranged between 0.6 and 3.1 mg/L (as NO_3^-) during storms, with a maximum observed value of 4.3 mg/L. The USEPA (2017) drinking water standard is 45 mg/L as NO_3^- or 10 mg/L as NO_3^--N. Other soil solute concentrations declined after logging because of dilution. Phosphorus losses in streamflow were slightly higher after logging, but no significant change was found in soil P pools. Organic-rich sediment from the reference watersheds held a higher concentration of N than organic-poor sediment from clearcut watersheds, but sediment loads increased significantly after logging. Concentrations in suspended sediment of N (1.2 to 6.5 g/kg) and P (1.1 to 1.5 g/kg) were relatively high, indicating that increased erosion could lead to considerable nutrient loss following logging. Dahlgren (1998a) noted that N, P, and sulfur (S) are likely to be the most limiting nutrients for forest growth at the site. Gaseous losses via denitrification were found to be nearly an order of magnitude higher in a clearcut North Fork subwatershed several decades after logging than in a reference watershed (Mnich and Houlton 2016).

Keppeler et al. (1994) reported peak piezometric pressures that were 9 to 35 percent above prelogging levels at a clearcut site in the North Fork, and Ziemer (1992) found peak pipeflow was ~3.7 times greater than prior to harvest. These changes explain much of the difference that Dahlgren (1998a) found in soil and pipeflow nutrient concentrations between clearcut and forested sites. Storm runoff was found to increase after both South Fork tractor selection logging (Thomas 1990) and North Fork clearcutting (Lewis et al. 2001). Reid (2012) reevaluated South Fork data and found significant increases in peak flows across a range of discharges during the initial postlogging period; previous studies, which had grouped data from both the logging and postlogging period, had found significant changes only in small peaks. Wright et al. (1990) documented reductions in lag time for peak flows after South Fork logging. Ziemer (1998a) and Lewis et al. (2001) found increased peak flows across the range of storm sizes after North Fork clearcut logging. Results of the study were used to develop a peak flow prediction model that has been used to evaluate proposed logging plans in the region (Cafferata and Reid 2013). CCEW flow data were also used to test methods for estimating peak flows at ungaged sites (Cafferata et al. 2004, Cafferata and Reid 2013).

Annual water yields increased after both South Fork and North Fork logging (Keppeler 1998), while dry-season South Fork flows showed an initial increase followed by a lengthy reduction as regrowth progressed to below pretreatment levels 8 to 28 years after logging (Reid 2012). Reid and Lewis (2011) evaluated potential interactions between altered climate and logging as they may affect future dry-season flows at Caspar Creek. Reid and Lewis (2007, 2009) showed that reduced interception and transpiration are sufficient to explain observed changes in peak flows after North Fork logging. Later work evaluated the influence on dry-season flow of postlogging changes in interception and transpiration (Reid 2012).

Studies at CCEW have evaluated sediment inputs during roadbuilding (Krammes and Burns 1973), selection logging (Rice et al. 1979), and clearcut logging (Lewis et al. 2001). Other studies measured inputs from specific sources such as surface erosion (Barrett et al. 2012), gully erosion (Reid et al. 2010), and landslides (Cafferata and Spittler 1998, Reid and Keppeler 2012). Long-term monitoring showed renewed sediment increases from deterioration of old South Fork roads (Keppeler 2012), and sediment inputs are now being assessed from decommissioned roads. Early measurements of sediment from South Fork timber operations informed revisions to the California Forest Practice Rules, and CCEW data have been cited regularly in total maximum daily load (TMDL) documents, forest management plans, and other planning documents that address sediment concerns (Cafferata and Reid 2013).

Water temperature monitoring showed large increases in the South Fork during and after construction of a mainline road adjacent to the channel, with the maximum temperature at the downstream end of the study reach increasing from 13.9 to 21.1 °C (Burns 1972). Buffer strips prevented similar increases below a clearcut along a North Fork stream reach, with a daily maximum temperature of 16.1 °C (Cafferata 1990). Water temperatures recorded in the North Fork after logging were within the tolerable range for salmonids (Nakamoto 1998). Mean monthly dry-season stream temperatures did not exceed 14.6 °C. The South Fork channel continues to have relatively low levels of large wood after road construction, selection logging, and clearing of logging debris from the channel. Inputs of large wood along the North Fork increased after logging owing to blowdown in buffer zones exposed to increased wind at clearcut margins (Hilton 2012, Reid and Hilton 1998).

Graves and Burns (1970) suspected that high rates of juvenile salmonid emigration after South Fork road construction resulted from reduced habitat quality, but Nakamoto (1998) found no changes in salmonid populations attributable to North Fork logging. Bottorff and Knight (1996) documented increased postlogging macroinvertebrate density and diversity in the North Fork and concluded that changes in macroinvertebrates, algal growth, and leaf decay rates were consistent with some combination of increased temperatures, light, and nutrients after logging and not with an increase in sediment. The effects of specific influences could not be distinguished.

Reliability and Limitations of Findings

As with any long-term study, advances in monitoring technology both improve data quality and complicate comparisons between data collected during different periods. Long-term datasets thus need to be assessed during each application to assure that the attributes of interest are represented by an appropriately consistent record.

Studies that focused on understanding specific processes were most reliable for assessing causal mechanisms and produced results applicable to other sites with similar controlling factors. Because different processes respond to different controlling variables, areas over which results can be applied differ for different attributes. Cafferata and Reid (2013) described the areas of applicability for specific CCEW study results. Even within similar areas, transfer of quantitative results is most reliable if validation monitoring is done to test the application.

Studies that attempted to relate instream biological changes to specific causal mechanisms met with limited success owing to the variety of factors that influenced responses. Measurements were too few to identify specific causes for biological changes observed after South Fork road construction. During the second management experiment, Bottorff and Knight (1996) used a panel of response variables to try to identify causal mechanisms by comparing responses for different variables. However, logging was followed by a dry period, introducing an additional influence that complicated interpretation.

Results of long-term studies are sometimes dismissed as moot because land use practices and regulations change during the study period. However, if process mechanisms are understood, results can be applied under different management conditions by evaluating the influence of those new conditions on the causal mechanisms. In other cases, results are disregarded because experimental watersheds are often small. Studies of gradients in expression of changes over increasing scales (e.g., Lewis et al. 2001) allow likely effects to be estimated for larger areas. In any case, large watersheds are composed of smaller ones, so an understanding of changes in outputs from small watersheds can inform expectations of changes in larger basins.

Research Needs

The highest priority research need for the regulatory community related to N and P that might be filled by future studies at CCEW is a better understanding of how differences in riparian stand structure and composition affect seasonal light levels and nutrient availability that influence primary production and salmonid production.

Improved knowledge of these interactions between upland-riparian and instream nutrient dynamics would benefit regulatory agencies by providing a stronger scientific basis for establishing regulations for riparian zone management. Several aspects of this problem could be investigated by future research at CCEW. Long-term effects could be evaluated retrospectively by testing for differences in instream characteristics along South and North Fork Caspar Creek reaches that underwent different riparian disturbances in the past. Short-term effects could be identified during future CCEW experiments by testing the outcomes of different riparian vegetation management treatments on stream properties such as light levels, above- and belowground organic material inputs, primary productivity, and DO in low- to mid-order stream reaches. Scale effects could be assessed by comparing outcomes of riparian treatments across a range of channel sizes. Research to address this need, however, is not part of CCEW Experiment Three that is currently underway and would require additional resources to implement.

Other research questions of interest to the regulatory community in the region, although of lower priority, that might also be addressed through future research at CCEW include the following:

- What long-term effects does forest management have on nutrient cycling, sediment production, forest productivity, and their interactions?
- What effects do reduced inputs of marine-derived N and P, from declining salmonid runs, have on stream and riparian biological processes?
- What effects do chronic turbidity durations and spatial distributions at a watershed scale have on anadromous salmonid growth and survival.
- What factors affect headwater stream temperatures?
- How effective are current California Forest Practice Rules for meeting Basin Plan water quality objectives?
- How effective are aquatic restoration projects for improving habitat conditions and food resources for salmonids?
- What are reference conditions for microbial pathogen levels in North Coast watersheds that support urban and agricultural uses?
- Would more efficient sediment budgeting methods improve assessments of the effects of planned land uses on water quality, nutrient loads, and stream sedimentation?
- How does climate change, including extreme weather events, affect nutrient cycling?

Potential Utility to Water Quality Regulatory Agencies

Results of CCEW studies are often used by California state and federal regulatory agencies as a basis for understanding the impacts of logging practices on water quality in the region (Cafferata and Reid 2013). Results from CCEW research regarding management-related effects of timber harvesting are expected to apply to other watersheds that support second-growth coast redwood in similar settings, and the basic understanding of watershed processes provided by these studies is even more widely applicable.

Baseline and postharvest information on hydrology, sediment, nutrients, and other characteristics in the watersheds have been used in TMDL documents for watersheds in similar settings. Results have also been used by regulatory agencies to evaluate potential impacts of timber harvesting plans and other projects that require agency approval. Additionally, Basin Plan amendments have been informed by CCEW results.

Monitoring methods developed at CCEW have reduced the cost and increased the efficiency and accuracy of suspended sediment monitoring (Lewis and Eads 2009), and these methods have been widely applied to water quality monitoring programs elsewhere. In addition, results of CCEW studies have contributed to the development of analytical tools and methods now used by regulatory agencies in the region (Cafferata and Reid 2013).

Key points:

- Stream water N outputs increased after clearcut logging but quickly decreased again owing to rapid revegetation by coast redwood stump sprouts.
- Increased runoff after logging explained much of the change observed in stream nutrient concentrations, and altered NO_3^- concentrations in streams also reflected changes in soil solutes in the A and AB horizons, the portion of the soil profile that contributes most to subsurface lateral flows.
- Nitrate fluxes after clearcutting were low compared to some eastern U.S. watersheds, and stream water concentrations did not exceed drinking water standards.
- Sediment inputs showed an increase 20 years after timber operations ceased as the network of roads and skid trails deteriorated; these delayed inputs likely affected instream nutrient processing.
- Associating aquatic biological responses with particular management-related changes is complicated by the suite of interactions among physical, chemical, and biological components that may be altered by management treatments.
- Regulatory agencies would benefit from a better understanding of the influences of riparian stands on instream nutrient and organic matter dynamics in order to design appropriate riparian management strategies.

Biological Responses to Stream Nutrients Other Than N and P

Issues of Concern

Several regional nutrient issues do not involve N or P. There is growing interest in managing forest lands to enhance carbon (C) sequestration to mitigate global climate warming. In addition, S has been identified as a potential limiting nutrient in coast redwood forests. A third issue arises from the likely influx of air pollution from increased development in Asia. CCEW has few local air pollution sources upwind and may be ideally positioned to detect influxes of pollutants from Asian sources and to assess their effects on water quality.

Findings From Studies

Several studies relevant to C cycling have been carried out at CCEW. Sanderman and Amundson (2008) found that DOC leaches more deeply into soil and is retained longer under forest than in grassland, and they evaluated controls on soil CO_2 production and efflux (Sanderman and Amundsen 2010). Stream export of C from the watershed occurs both in solution and in the organic component of the suspended load, which Madej (2005) found to be appreciable at CCEW. Breakdown and transport of in-channel woody debris also results in C export, and measurements described by Hilton (2012) will allow evaluation of this component of C transport. Dahlgren (1998a) provided data on the distribution of C in biomass and soils in logged and forested subwatersheds.

Dahlgren (1998a) compared nutrient reservoirs with nutrient losses associated with logging and found that S, along with N and P, are the primary potential limiting nutrients in the CCEW forest. Sulfate (SO_4^{2-}), like NO_3^-, showed increased concentrations in stream water in the clearcut watershed. Unlike NO_3^-, however, SO_4^{2-} concentrations decreased during periods of high flow, indicating its source may be in the lower soil horizons.

Dose-Response Studies

There have been no dose-response studies at the CCEW related to nutrients other than N and P.

Reference Watersheds

The description of CCEW reference watersheds presented above also pertains to studies regarding nutrients other than N and P. The reference watershed located at the North Fork headwaters has been a principal source of data owing to the long-term hydrologic datasets available for that site. Dahlgren (1998a, 1998b) measured

SO_4^{2-}, calcium, magnesium, and potassium in this reference basin that were analogous to those already described for N and P. Sanderman (2007) carried out his study of DOC at the site.

Research Needs

The highest priority research need of the regulatory community, not directly related to N and P, that might be filled by future research at CCEW is more information on the effects of different silvicultural strategies on long-term rates of C sequestration in soils and on fluvial export of dissolved and particulate carbon. Results from such studies would provide regulatory agencies with a stronger scientific basis for considering C sequestration and greenhouse gas production in developing rules and guidelines for forest practices. Future studies at CCEW that might contribute to filling this gap would include developing more detailed C budgets for subbasins with different management treatments and comparing those results with similar budgets for unmanaged reference subbasins. At CCEW, large POM is trapped in the weir ponds, facilitating study of seasonal transport rates, and fine POM could be evaluated in samples taken routinely for sediment evaluation. Contrasts in riparian vegetation between the North and South Forks would allow for differences in organic C inputs from an alder-rich riparian zone to be compared with those from a coniferous riparian zone. Long-term silvicultural influences could be evaluated by comparing soil carbon storage across a range of silvicultural treatments in the watersheds ranging from past management treatments to those imposed in the next round of large-scale experiments. Monitoring emissions of greenhouse gasses, CO_2, methane and nitrogen oxide (N_2O), from streams and soils under different treatments could improve assessments of C fluxes. Research to address this need, however, is not part of the CCEW Experiment Three that is currently underway and would require additional resources to implement.

Other lower priority information gaps of interest to regulators that might be filled at CCEW include the following:

- How is POM transformed in stream channels, and how does it affect instream productivity, DO levels, and denitrification, including N_2O production?
- Will losses of S associated with forest management significantly limit future growth in coast redwood forests?
- Is the region receiving significant air pollution from Asia, and what are the implications of this pollution for water quality?

Potential Utility to Water Quality Regulatory Agencies

While CCEW clearcutting did not result in detectable short-term decreases in soil C (Dahlgren 1998b), C sequestration rates remain an important issue when considering contemporary impacts of forest management. Additionally, a study of nutrients removed in the biomass harvested indicated that S may be a critical nutrient when considering long-term forest productivity, meaning that regulatory agencies should be aware of potential future issues regarding forest S budgets. Information gained about the behavior of S in streams may lead to development of efficient protocols for monitoring S loss after logging.

Key points:

- It will be important to better understand sulfur cycling in these forests, as sulfur may be a limiting nutrient affected by forest management.
- Organic material is a significant portion of the sediment load at Caspar Creek.
- A high-priority research need for the regulatory community is improved understanding of effects of management on C cycling in these forests.

Overview and Synthesis

CCEW research has provided a scientific basis for understanding N and P fluxes in the watersheds and the effects of logging on those fluxes. Results indicate that stump sprouting of coast redwood quickly curtails increased nutrient export from logged sites. However, removal of timber over multiple logging cycles may lead to future nutrient deficits, and this could influence nutrient loads in streams. The effects on specific nutrient fluxes are strongly influenced by hydrologic changes caused by logging, both within soils and in streams. Understanding management-related changes in runoff and sediment input thus is key to predicting management-related changes in nutrient routing in this region.

Logging affected Caspar Creek flow primarily through reduced rainfall interception and transpiration. Long-term monitoring indicates that selection logging in the South Fork caused short-term increases in dry-season flows, but rapid regrowth curtailed those increases after nearly a decade and then led to a protracted period of summer flows that were lower than they were before cutting. Long-term monitoring showed renewed sediment inputs to streams 30 years after South Fork logging as the old road system deteriorated.

Aquatic biological responses to CCEW logging reflect a combination of altered flow, sediment loads, nutrient loads, light levels, woody debris inputs, organic material loads, and temperature. Not only do these factors individually affect biological stream processes and aquatic ecosystems, but each affects the biological response to others. Untangling the web of interactions would require a combination of controlled experiments in both field and laboratory settings.

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