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Sediment loads and erosion in forest headwater streams of the Sierra Nevada, California

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Abstract Defining best management practices for forests requires quantification of the variability of stream sediment loads for managed and unmanaged forest conditions and their associated sediment sources. Although "best management practices" are used, the public has concerns about effects from forest restoration activities and commercial timber harvests. It is necessary to know the current and/or natural range of variability to be able to determine if management activity has a significant negative impact; only long-term research can provide such data. The Forest Service in the United States has such long-term watershed research. An annual sediment load from a watershed is determined by emptying a sediment basin located in the stream channel at the end of a water year. Sediment fences, stream bank pins, survey techniques, and turbidity sensors provide measurements that can be used to determine the sources of sediment. The importance of having an undisturbed watershed for "natural range of variability" to compare with watersheds previously or currently under active management is illustrated. For example, at the Kings River Experimental Watersheds one of the managed watersheds in the rain and snow zone, produced 1.8, 15.2, and 18.7 kg/ha for water years 2004, 2005, and 2006, respectively. The increase in sediment accumulation correlates with an increase in yearly precipitation. The undisturbed watershed and the snow-dominated watersheds produce similar, and sometimes higher, sediment loads for these same years.

Key words erosion; sediment loads; headwater streams; forest management

INTRODUCTION

The ability to quantify best management practices for forests requires quantification of the variability of stream sediment loads for managed and unmanaged forest conditions and their associated sediment sources. Although "best management practices" are used, the public has concerns about effects from restoration activities and commercial timber harvests. Long-term watershed research, such as that conducted by the US Forest Service, can provide such data. Both mechanical thinning and prescribed fire can be used to restore forests in the Sierra Nevada to pre-fire suppression conditions; mechanical treatments can be effective tools to modify stand structure and influence subsequent fire severity and extent. North *et al.* (2009) review of the literature shows that prescribed fire can be ineffective at restoring resilience; in many stands, mechanical thinning followed by prescribed fire may be necessary to achieve forest resilience much faster than with prescribed fire alone. Although restoration is a positive activity, there are some concerns about short-term negative effects from soil erosion and sedimentation on water quality and stream organisms.

The Sierra Nevada is an ideal location to examine links between erosion, chemical weathering and climate because variations in other factors that strongly influence soil development, such as tectonics and lithology, are minimal (Dixon *et al.*, 2009). Prior to the Kings River Experimental Watersheds (KREW), little was known about sediment erosion rates for either undisturbed or managed watersheds in the southern Sierra Nevada. This experimental watershed is the most recent one established by the Forest Service, and is an example of the type of information that can be produced by Experimental Forests and Ranges of the US Department of Agriculture, Forest Service (Adams *et al.*, 2008).

The KREW project has several research objectives for sediments.

(1) To quantify the variability in sediment loads for headwater streams of the Sierra Nevada
(2) To identify the sources of sediment for headwater streams and quantify their relative contribution to the overall sediment load.
(3) To compare sediment loads from an undisturbed watershed to those of managed watersheds.

(4) To identify any differences in sediment sources and loads between watersheds with precipitation dominated by snow and those receiving both rain and snow.

This paper addresses objectives (1), (3) and (4) in detail. Some preliminary data are presented about objective (2).

STUDY AREA

The Kings River Experimental Watersheds (KREW) were established in 2000 to develop data on the variability of headwater ecosystems of the southern Sierra Nevada and to study the effects of management activities designed to improve the sustainability of the forest ecosystem. This long-term experimental study is located on the Sierra National Forest in the Kings River drainage (Fig. 1). Two sites were selected, Providence site and Bull site, that each contain four adjacent watersheds. The lower elevation Providence site (1485–2115 m elevation) receives both rain and snow while the higher elevation Bull site (2145–2490 m elevation) is snow dominated. All the streams are perennial and are 1–3 m in width. The watersheds are conifer-dominated forest with meadows and granite rock outcrops. A unique feature is that one of the watersheds (T003) has no disturbance from roads or logging and thus serves as an excellent source of data for natural sediment loads and their range of variability over time.

The hillslopes are underlain by granitic rocks and are on unglaciated terrain. Three soil series dominate the landscape: Cagwin, Gerle-Cagwin, and Shaver. The Shaver soils are dominant at the Providence site, and the Cagwin soils are dominant at the Bull site. All of these soils have the same “maximum erosion hazard” rating: moderate on 5–35% slopes and high on 35–65% slopes (Giger & Schmitt, 1993). This factor is designed to indicate the relative risk of accelerated sheet

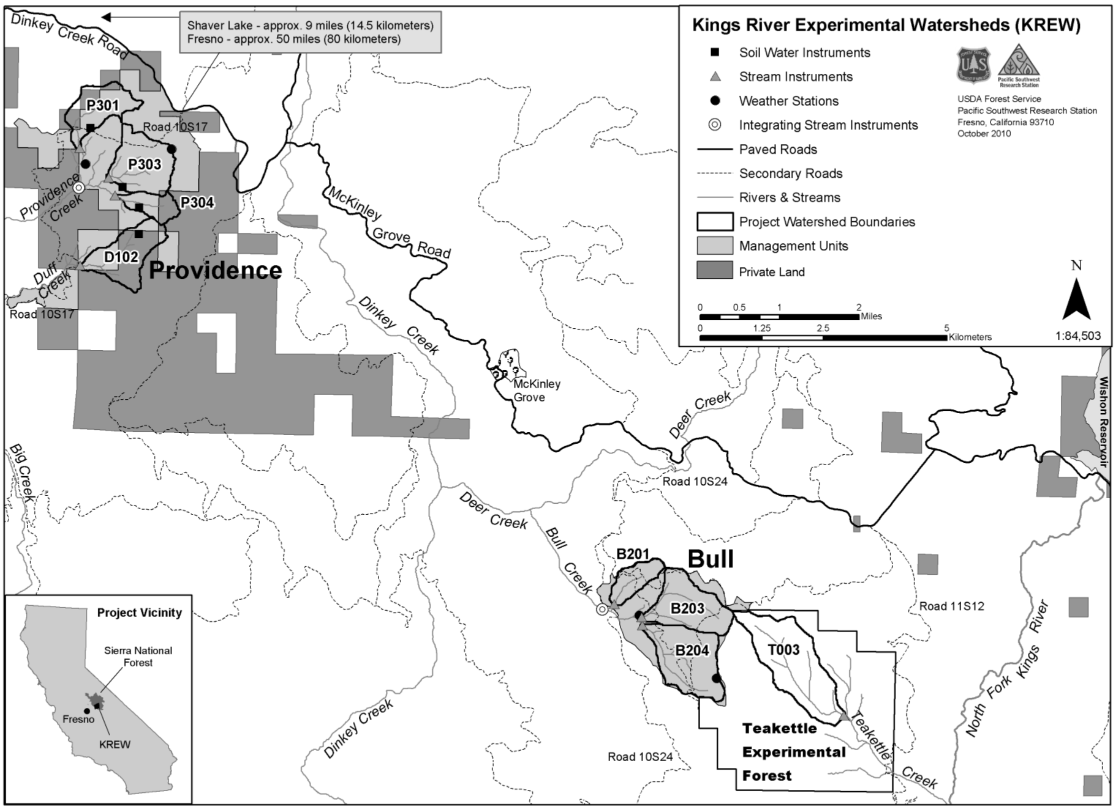

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Fig. 1 The Kings River Experimental Watersheds (KREW) research is located on headwater tributaries of the Kings River in the Sierra Nevada Mountains of California. KREW consists of two sites approx. 15 km apart: Providence shown at the top of the figure and Bull shown at the bottom of the figure.

and rill erosion with little or no vegetation cover for the long-term average occurrence of 2-year, 6-h storm events. The watersheds range in size from 49 to 228 ha, and the streams range in length from 800 to 3000 m. The average channel slope is fairly consistent across all streams at 11–12%, except that D102 and T003 have steeper headwaters (Fig. 2).

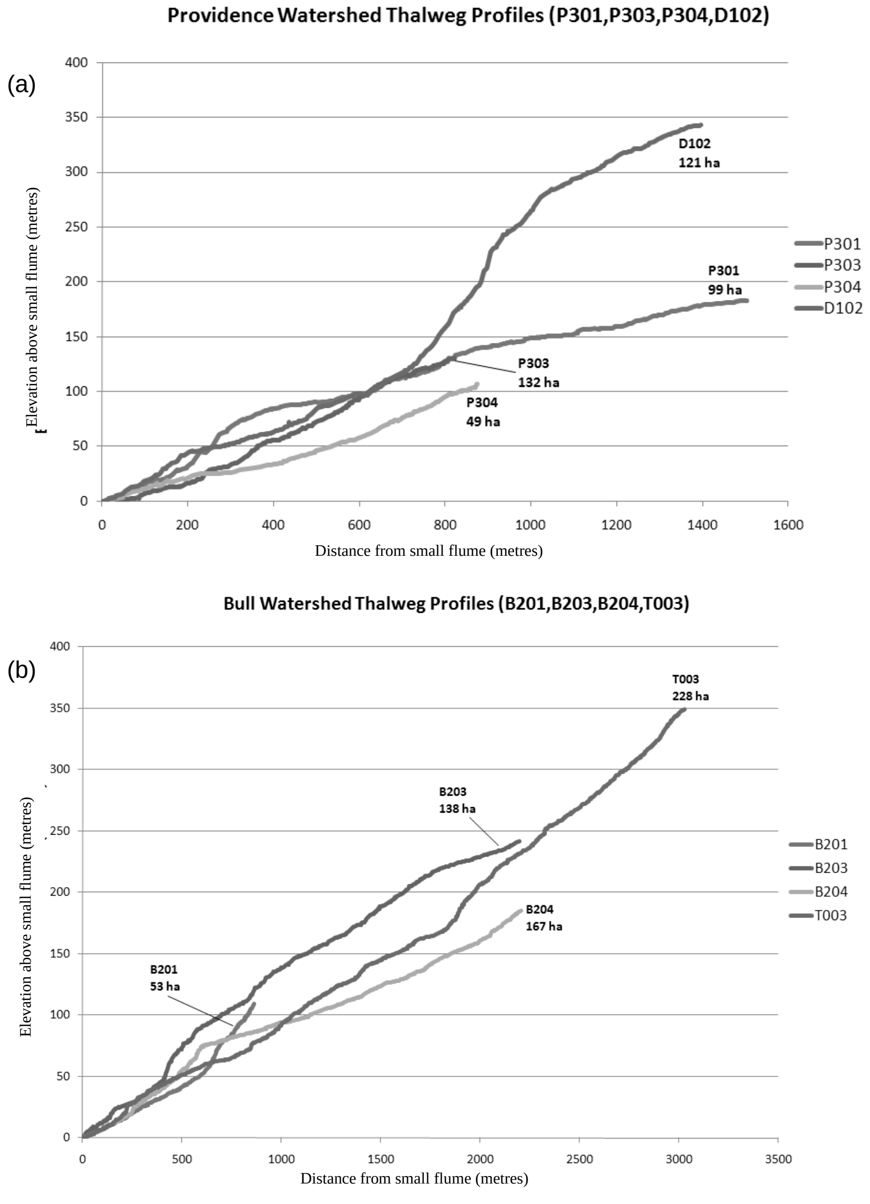

Fig. 2 Longitudinal profiles were created using survey methods for Providence site watersheds (a) and Bull site watersheds (b).

METHODS

Each of the eight streams has either flumes or weirs and multiple instruments for measuring discharge. Precipitation and other weather attributes are measured at four locations (Fig. 1). Hunsaker *et al.* (2012) describe the KREW stream discharge and weather station instruments in detail and discuss measurement variability and patterns. This area also hosts the Southern Sierra Critical Zone Observatory (SSCZO) which has additional instruments at the Providence site to quantify water balance processes (Bales *et al.*, 2011).

Each stream has a constructed sediment basin that is emptied by hand each fall to measure the annual sediment load from the watershed. The proportion of organic matter and the particle size distribution of the sediment are determined for each basin. Large woody materials (cones, bark, and twigs/limbs greater than 1 cm in diameter and 10 cm in length) are removed separately from the sediment, weighed wet, and a representative sample is dried and weighed to provide a dry weight of large wood. A proportional wet sample is taken from each bucket of sediment removed from the basin. Water is decanted from this sample, the sample is mixed well and subsampled for processing. The percent of organic and mineral materials are determined by floating the organics with water and skimming them off, as well as combusting the organics at high temperature. Particle size is determined by sieving. Repeated survey measurements in each watershed allow estimation of the proportion of the sediment load that comes from various sources such as stream banks and headcuts. Sediment fences provide measurements of the annual erosion from roads and undisturbed hillslope areas in the watersheds (Stafford, 2011). Sensors (Forest Technology Systems DTS-12) in the streams provide continuous measurements of turbidity in Nephelometric Turbidity Units (NTU) which can be used to estimate the suspended sediment concentration in the streams. For the Providence streams, good relationships between turbidity and suspended sediment concentrations ($r^2 = 0.82$ to 0.97) were developed; these relationships will allow the estimation of annual and event total suspended sediment loads.

RESULTS

Precipitation amount and timing were very similar for all four KREW weather stations (75–200 cm depending on year), despite the nearly 700 m difference in elevation (Fig. 3). Armstrong & Stidd (1967) show that precipitation on the west side of the Sierra Nevada (American River Basin) reaches a maximum at about 1200 m (50 years of data for 65 gauges) thus supporting the observation of similar precipitation at the elevations of the Providence and Bull

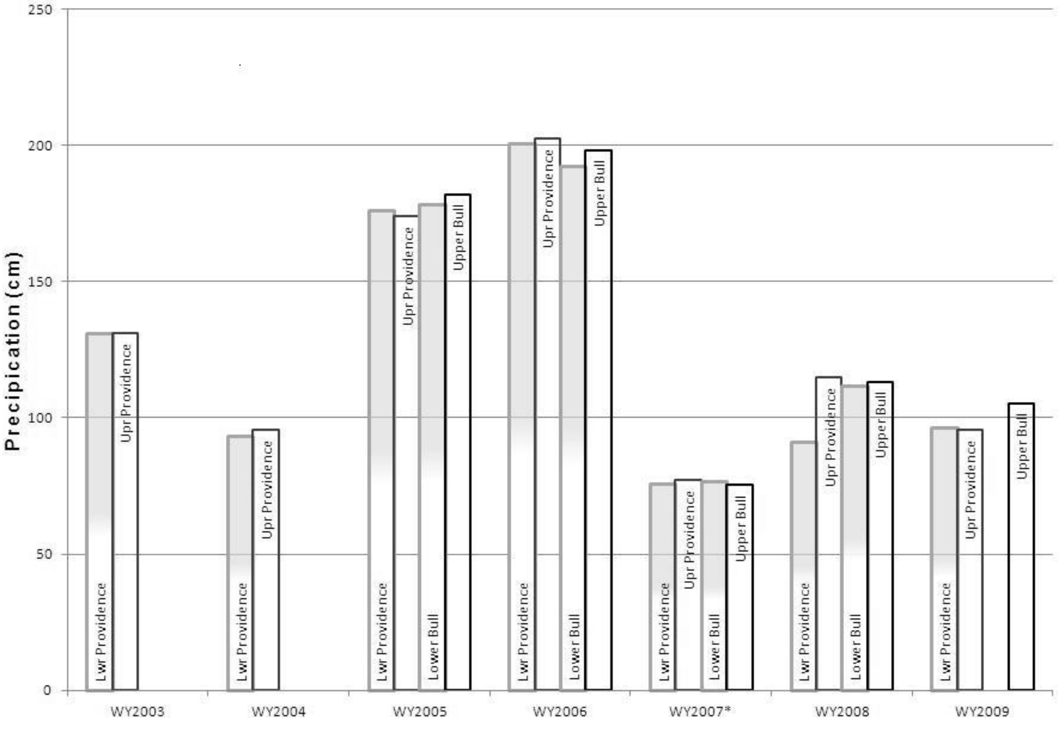

Fig. 3 The total annual precipitation for the first seven years is compared for the four KREW weather stations. Water Years (WY) 2005 and 2006 had very high precipitation while 2007 had below average precipitation. The Bull weather stations were not completed until 2005; the lower Bull station had instrument problems in 2009.

catchments. The important difference about precipitation is that the fraction of precipitation that fell as snow ranges from 75 to 90% at the Bull site, and from 35 to 60% at the Providence site. The stream discharge pattern reflects this difference in precipitation type with the larger snow-dominated watersheds (T003, B203, and B204) having about two or three times the stream discharge of other watersheds (Fig. 4). Stream annual discharge has three patterns at KREW: high flow streams (B203, B204, T003), moderate flow streams (P301, P303, D102), and lowest flow streams (P304 and B201). The latter are the shortest streams with the smallest watersheds (Fig. 2).

Seven years of research on sediment yield, suspended sediment, and sediment sources on the eight streams in KREW establishes the variability of sediment conditions in the headwaters of the southern Sierra Nevada. The highly variable data for stream sediment loads were log transformed to meet the requirements for statistical analyses. An analysis of variance was performed using site (Providence and Bull) as a blocking factor and the individual streams as subsamples within a site. Sample year was included as a main effect. Sediment load differed significantly between years due to differences in precipitation amount and event intensity, which are the primary forces for moving soil and sediment. There is no main effect of site, nor is there any site by year interaction ($P < 0.05$).

The mineral mass loads (normalized by watershed size) of the streams show fairly parallel histories for wet and dry years (Fig. 5). During the period of record, very wet (2005 and 2006) and dry years (2007) correspond well to the highest and lowest sediment loads, respectively. The P304 stream consistently has the highest load, and the P301 stream has the lowest load. The T003 stream has one of the higher sediment loads even though its watershed has no roads or past logging activities to cause soil disturbance. Although forest management histories differ among the other seven watersheds, minimal new human disturbance has occurred within the past 15 years. The similarities in average annual sediment loads, 2 to 17 kg/ha, for seven of the streams are not surprising given the deep litter layers and good canopy cover of the landscape (Table 1). Data from hillslope sediment fences support this observation as they usually collect no sediment during the year (Stafford, 2011).

One research objective is to quantify the relative contribution of different sources of stream sediment. Stream banks, headcuts, and road and hillslope erosion have been measured. Yearly and multiple year headcut contributions are compared to yearly bank erosion (Table 1). For the P304 stream, the volume of sediment from stream banks (1.4 m^3) is higher than from headcuts (0.8 m^3) when short-term measurements are compared; however, the annual volume of sediment from

Table 1 Stream sediment loads compared to sediment sources (stream banks and headcuts). Stream bank data are from Martin (2009).

Stream code	Sediment load (average annual 2003–2009)		Stream banks (2005–2006)			Headcuts (2003–2005)		Headcuts (2003–2009)
	Normalized weight (kg/ha ± sd)	Volume (m^3)	Mean bank height (m)	Volume eroded (m^3/year)	Normalized eroded volume 10^{-3} (m^3/m)	Volume eroded in 2 years (m^3)	Normalized eroded volume 10^{-3} (m^3/m)	Volume eroded in 6 years (m^3)
P301	6 ± 8	0.6	0.60	10.0	5.9	4.2 (2.1/year)	44.3	
P303	2 ± 3	0.3	0.65	20.9	18.7	3.3 (1.6/year)	50.1	
P304	61 ± 61	3.0	0.88	1.4	3.3	1.6 (0.8/year)	34.8	18.6 (3.1/year)
D102	17 ± 20	2.1	0.78	23.6	13.5	2.3 (1.2/year)	28.1	
B201	13 ± 14	0.7	nd	nd	nd	nd	nd	nd
B203	10 ± 12	1.4	nd	nd	nd	nd	nd	nd
B204	8 ± 11	1.4	nd	nd	nd	nd	nd	nd
T003	16 ± 21	3.6	nd	nd	nd	nd	nd	nd

nd = no data.

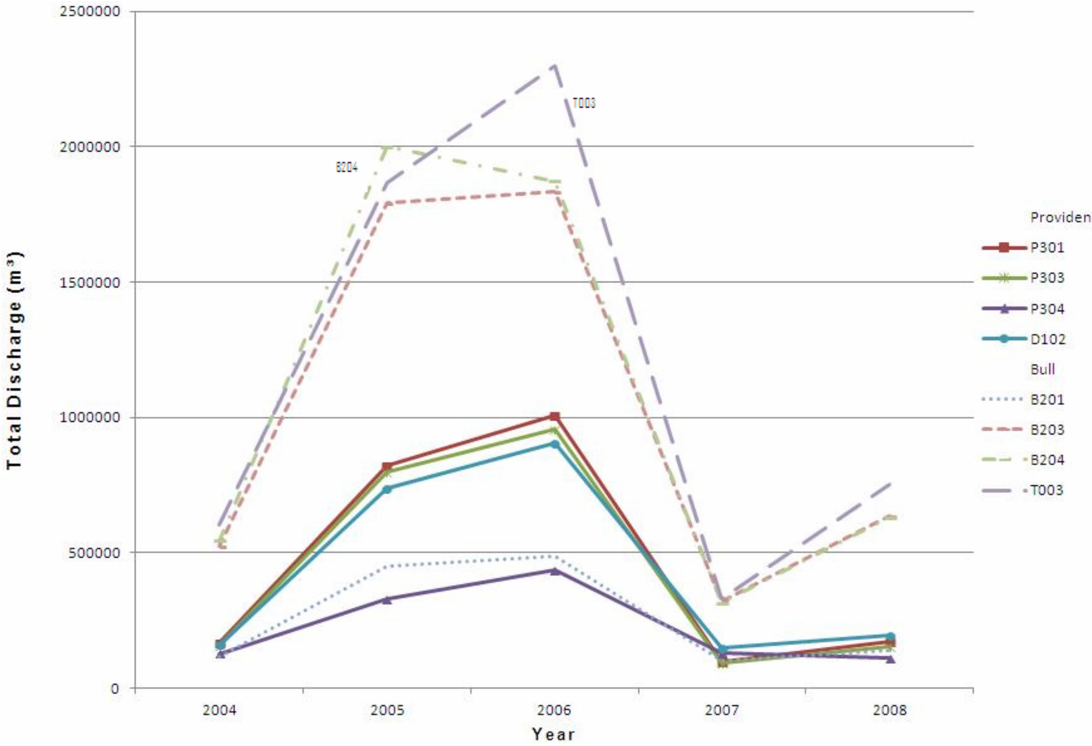

Fig. 4 Total annual discharge for the eight KREW watersheds is compared for the first seven years of data collection. These data establish a consistent pattern of three groups among the streams and characterize their natural range of variability for discharge.

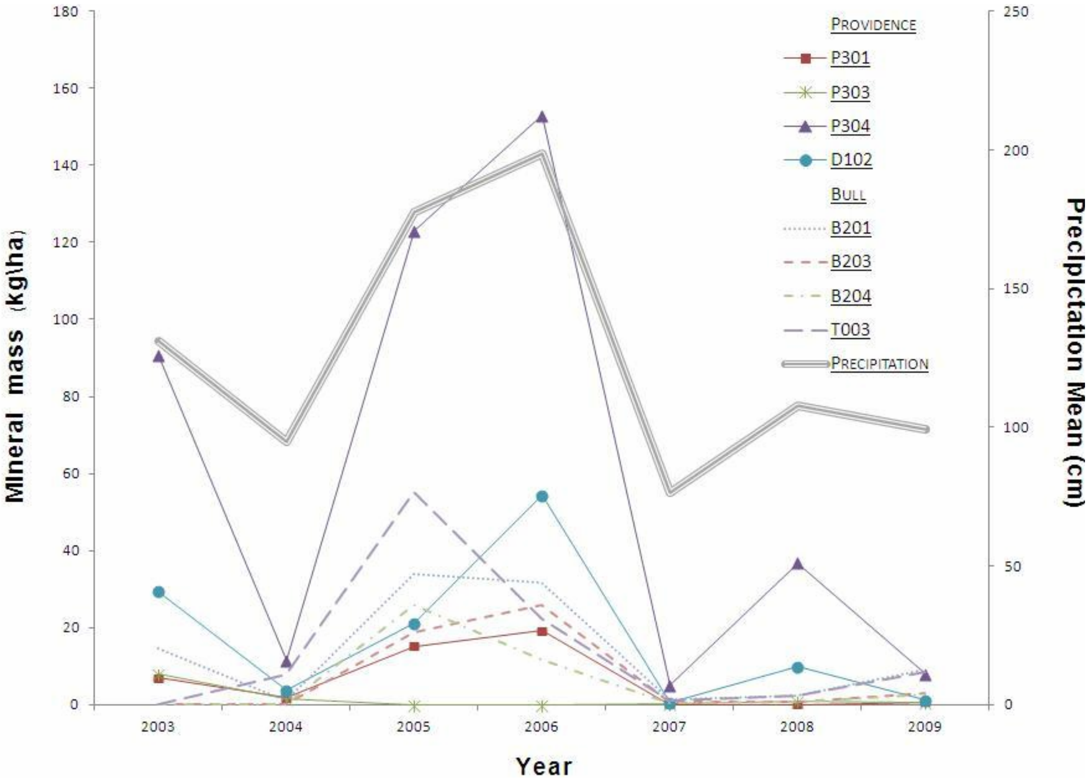

Fig. 5 Mineral mass loads for the eight KREW streams with sediment basins for water years 2003–2009. Stream sediment loads are correlated positively with total annual precipitation and discharge (Figs 3 and 4). The precipitation values shown are the mean of that measured at all four weather stations.

headcuts is almost four times higher (3.1 m^3) when averaged over a 6-year period. These source contributions seem reasonable when compared to the average annual volume of 3.0 m^3 for P304 and the high year-to-year variability. Data have been collected to develop the contribution from road and hillslope erosion. Eventually soil erosion and sediment loads from these baseline years will be compared to measurements taken after mechanical tree thinning and prescribed burning.

Three of the streams in the Providence site carry only 3–28% of the sediment load carried by the adjacent P304 stream (Table 1). The reason for this difference may be explained by rock (saprolite) weathering processes and the rock content of soil. The P304 watershed has no large exposed rock outcrops unlike its companion watersheds (Fig. 1). The percent of rock in the coarse soil (particle size >2 mm) is <20% for P304 while the other Providence watersheds have 30–50% rock in their coarse soil (Johnson *et al.*, 2011). Rock fragment abundance in soil at KREW may be

Table 2 Annual watershed sediment load collected for seven years in sediment basins, expressed as percent[a] gravel, sand, and silt. Watersheds are arranged in the table from highest to lowest elevation.

Stream code and sediment size	2003	2004	2005	2006	2007	2008	2009	Average
B203								
Gravel[b]	nb[c]	nb	19	31	24	36	43	31
Sand[b]	nb	nb	80	68	72	62	55	67
Silt[b]	nb	nb	1	1	4	2	2	2
B204								
Gravel	nb	nb	8	7	7	2	5	6
Sand	nb	nb	90	92	82	89	87	88
Silt	nb	nb	2	1	11	9	8	6
T003								
Gravel	nb	20	36	7	13	2	18	16
Sand	nb	74	62	86	80	76	72	75
Silt	nb	5	2	7	7	22	10	9
B201								
Gravel	9	3	12	6	3	1	4	6
Sand	85	80	82	88	81	78	81	82
Silt	6	17	6	6	16	21	15	12
P301								
Gravel	20	26	18	33	10	2	1	16
Sand	78	68	79	65	84	87	68	76
Silt	2	4	3	2	6	11	31	8
P303								
Gravel	26	13	nd[d]	nd	10	2	4	11
Sand	72	83	nd	nd	84	83	66	77
Silt	2	5	nd	nd	6	15	30	12
P304								
Gravel	4	2	3	6	1	2	1	3
Sand	88	79	89	88	72	86	65	81
Silt	7	19	8	6	27	12	34	16
D102								
Gravel	11	9	6	25	5	8	3	10
Sand	84	81	88	73	76	86	73	80
Silt	5	9	6	2	19	6	24	10

[a] The percentage values are adjusted if >0.5% of soil is lost during the processing; loss is usually during sieving. [b] Gravel is defined as particles >2 mm, sand is between 2 mm and 0.063 mm, and silt is <0.063 mm. [c] nb = basin was not constructed in this year. [d] nd = no data for this year because sediment basin failed during a storm.

inversely related to erosion rate. Riebe *et al.* (2001) showed that climate (temperature and precipitation) only weakly regulates non-glacial erosion rates in mountainous granitic terrain of the Sierra Nevada. Long-term erosion rates for KREW, based on previous cosmogenic nuclide research, are probably about 30–40 mm per 1000 years (Riebe *et al.*, 2001; Dixon *et al.*, 2009). Ongoing research on chemical depletion of rocks by weathering will help address the measured differences in stream sediment loads and the underlying processes of soil formation.

Several of the streams are substantially different with regard to the amount of silt (<0.063 mm), sand (between 2 mm and 0.063 mm), and gravel (>2 mm) in their sediment (Table 2). The P304 stream has the highest average annual proportion of silt (16%), and P303 and B201 both have 12% silt in their sediments. All the rest of the streams have 10% or less silt in their stream sediment. The B203 stream has substantially more gravel (31%) in its average annual sediment. Gravel makes up 16% of the sediment in P301 and T003. The other five streams have 11% or less gravel in their sediments. The remaining fraction of the sediment is classified as sand and makes up 67–88% of the average annual sediment; B204 has the highest proportion of sand (88%). The B203 stream has the most coarse sediment, with only 2% in silt, 67% in sand, and 31% in gravel.

Coarse and fine particulate organic matter, on average, makes up 30–50% of the material trapped in most of the sediment basins. P304 and B201 have the lowest average proportion of organics (19 and 28%, respectively) and the lowest annual stream discharge. The P304 stream also has the highest average annual sediment load when normalized by watershed size (61 kg/ha).

DISCUSSION AND CONCLUSIONS

Prior to the establishment of the Kings River Experimental Watersheds, little was known about sediment erosion rates for either undisturbed or managed watersheds in the southern Sierra Nevada. Many factors contribute to the amount of soil that erodes from land. Forest cover maintains very low erosion rates, and consequently low suspended sediment concentrations in streams. Lee (1980) discusses factors that protect soil from erosion and those that contribute to erosion. Forest litter protects the soil from raindrop impact and helps maintain high infiltration capacity, so surface erosion is seldom a serious problem in undisturbed forests. Tree roots also help bind the soil mass, reducing the hazard of mass soil movements even on steep slopes. Sediment yield per unit area generally decreases with catchment size; however, smaller headwater catchments are also steeper. Lee (1980) states that watershed areas less than 25 km^2 can produce an average annual sediment yield of 18 m^3/ha. The KREW watershed sediment yields are much lower than that; however, that amount will increase once total annual suspended sediment loads are estimated. The year to year variability is large and, as is expected, corresponds well with the amount of precipitation in a given year. It is logical that these streams are not seeing high sediment loads; no new roads or logging activities have occurred recently, the forest floor litter layer is quite deep in most places due to fire suppression, and the area has few landslides. Although slopes are steep, soils are coarse and not highly erosive, and much of the precipitation occurs as snow.

Headwater streams like those in KREW (first and second order) are usually heterotrophic (community respiration exceeds photosynthesis), and the heterotrophic organisms like stream invertebrates derive their energy from living or dead organic matter. Most of this coarse and fine particulate organic matter comes from terrestrial vegetation (Bisson & Bilby, 1998). Thus the high percentage of fine and coarse organic matter (30–50%) in the KREW stream sediment is expected for headwater streams. It is logical for a stream like B201, which flows mostly through an open meadow, to have less organic matter because there are few trees to produce litter. Tree canopy cover near other streams is very high.

For watersheds with very similar landscape characteristics, the variability in sediment loads and composition among the eight watersheds is large. The smallest watersheds in KREW (P304 and B201) consistently have the largest sediment loads and the lowest annual stream discharge; however, these streams also are down cutting and thus have exposed banks that can erode. P304 soils have fewer rocks to the one metre depth, and the watershed has less exposed granite. Perhaps more soil provides more opportunity for erosion. Portions of the streambeds for many of the other KREW streams are exposed bedrock and therefore the stream cannot down cut and erode new sediment from these streambed areas. The P304 watershed has a long narrow shape (Fig. 1) compared to its companion watersheds, and thus soil has less distance to travel to get to the stream. A large proportion of the B201 stream is in a meadow which has collected fine silt. Thus some reasons for these differences can be observed and hypothesized; however, the much larger sediment load for P304 remains to be totally explained. Seven years of data provide an estimate of the "natural range of variability in sediment loads" from the undisturbed watershed (T003), and it is interesting that this stream carries a similar and sometimes higher sediment load than six of the watersheds that have a logging history with roads and other forest management activities. It is easy to see the usefulness of long-term watershed research, such as that maintained by the Forest Service in the United States, for characterizing variability, understanding landscape processes, and quantifying the effects of management activities.

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