Biogeosciences Discuss., 12, 2491–2532, 2015
www.biogeosciences-discuss.net/12/2491/2015/
doi:10.5194/bgd-12-2491-2015

Biogeosciences Discussions
Open Access

Soil carbon and nitrogen erosion in forested catchments: implications for erosion-induced terrestrial carbon sequestration

E. Stacy[1], S. C. Hart[1,2], C. T. Hunsaker[4], D. W. Johnson[3], and A. A. Berhe[1,2]

[1]Environmental Systems Graduate Group, University of California, Merced, CA, USA
[2]Life & Environmental Sciences and the Sierra Nevada Research Institute, University of California, Merced, CA, USA
[3]University of Nevada, Reno, USA
[4]Pacific Southwest Research Station, US Forest Service, Albany, USA

Received: 20 October 2014 – Accepted: 23 December 2014 – Published: 4 February 2015

Correspondence to: E. Stacy (estacy@ucmerced.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Soil erosion plays important roles in organic matter (OM) storage and persistence in dynamic landscapes. The biogeochemical implication of soil erosion has been a focus of a growing number of studies over the last two decades. However, most of the available studies are conducted in agricultural systems or grasslands, and hence very little information is available on rate and nature of soil organic matter (SOM) eroded from forested upland ecosystems. In the southern parts of the Sierra Nevada Mountains in California, we determined the rate of carbon (C) and nitrogen (N) eroded from two sets of catchments under different climatic conditions to determine how the amount and distribution of precipitation affects lateral distribution of topsoil and associated SOM. We quantified sediment and SOM exported annually (for water years 2005–2011) from four low-order, snow-dominated catchments, and four low-order catchments that receive a mix of rain, and snow and compared it to soil at three different landform positions from the source slopes to determine if there is selective transport of some soil OM components. We found that the amount of sediment exported varied from 0.4 to 177 kg N ha^{-1}, while export of particulate C was between 0.025 and 4.2 kg C ha^{-1}, compared to export of particulate N that was between 0.001 and 0.04 kg ha^{-1}. Sediment yield and composition showed high interannual variation, with higher C and N concentrations in sediment collected in drier years. In our study catchments, erosion laterally mobilized OM-rich topsoil and litter material, some of which readily enters streams owing to the topography in these catchments that includes steep slopes adjacent to stream channels. Annual lateral sediment mass, C, and N fluxes were positively and strongly correlated with stream flows. Our results suggest that variability in climate, represented by stream discharge, is a primary factor controlling the magnitude of C and N eroded from upland temperature forest catchments.

1 Introduction

Water-driven soil erosion is an important global process that transports on the order of 75 Gt of sediment and 1–5 Gt carbon (C) annually (Stallard, 1998; Berhe et al., 2007). Typically, 70–90 % of topsoil material mobilized by soil erosion is deposited within the same or an adjacent catchment (Stallard, 1998). The processes of soil erosion and terrestrial sedimentation have been a focus of a growing number of studies because of their potential to induce a net sink for atmospheric carbon dioxide (CO_2). Erosion can lead to terrestrial C sequestration if erosional loss of soil C from slopes is more than offset by stabilization of eroded C in depositional landform positions and/or at least partial replacement of eroded C by production of new photosynthate within the eroding catchment (Harden et al., 1999, 2008; Nadeu et al., 2012; Sanderman and Chappell, 2013; Stallard, 1998; Berhe et al., 2007). Eroded organic matter (OM) can be stabilized in low-lying depositional landform positions due to burial, aggregation, and sorption of OM on the surfaces of reactive soil minerals (Berhe et al., 2012a). Accumulation of organic- and nutrient-rich topsoil eroded from slopes in depositional landform positions also leads to increases in net primary productivity (NPP) and input of new soil organic matter (SOM) from production of new photosynthate to the soil C pool (Yoo et al., 2005; Berhe et al., 2008; Parfitt et al., 2013). Conversely, the loss of OM from eroding locations reduces NPP in the affected slopes due to reduction in nutrient stocks, soil water holding capacity, and soil depth. Hence, soil C and N budgets cannot be accurately assessed without considering the magnitude and impacts of lateral distribution of SOM (i.e., erosional efflux and depositional influx to any given SOM pool).

Soil erosion is highly variable spatially and temporally (Anderson and Lockaby, 2011). Erosion can mobilize soil minerals and OM from different slope positions or soil depths depending on the nature of erosion (sheet, rill vs. gully erosion) and available energy for transport. Higher frequency of rainstorms and rain-on-snow events that are anticipated with changes in climate (IPCC, 2007) will provide greater force to detach and transport

BGD
12, 2491–2532, 2015

sediment from the soil overall and potentially form channels that scour deeper soil layers. Typically surface erosion processes preferentially move mineral-associated OM and fine particulate OM over short distances – distances comparable to the that which eroded topsoil travels to a rill (Wang et al., 2013). Conversely, channeled water has more force to move larger soil particles and aggregates. In contrast to sheet erosion, rill and especially gully erosion transport material from deeper soil horizons leading to mobilization of sediment with low C concentrations (Boix-Fayos et al., 2009; Nadeu et al., 2011).

Episodic events, such as single storms or an extreme weather season, can mobilize large amounts of sediment or mobilize sediment from distinct landform positions of a hillslope, making it challenging to create conceptual or numerical models that can easily scale up across time and space (Kirkby, 2010). Furthermore, determining the effect of changing climate on erosion of soil and associated SOM is currently made difficult by shortage of data (Kirkby, 2010). There is lack of long-term data on how rates of sediment, C, and N erosion and export at the scale of hillslopes or catchments change over annual or decadal timescales. Spatial complexity in estimating rates of soil and associated OM distribution is also compounded further by the lack of information on the nature of OM that is mobilized by erosion and its fate. Here, we focus on determining the nature and magnitude of the sediment and associated OM that is exported out of forested upland catchments in temperate ecosystems to aid in the prediction of how climate regulates lateral export of eroded OM out of catchments.

The nature of erosion processes in forested ecosystems found in upland low-order catchments is inherently different than erosion that occurs in other types of ecosystems or geomorphic settings. In landscapes that have experienced little anthropogenic disturbance, such as upland forests in the Sierra Nevada Mountains, material transported by erosion is characterized by high proportion of undecomposed OM and high concentration of C in mineral soil, compared to agricultural or rangelands systems. The transport distance for eroded topsoil material (from source slopes to streams) in these upland forest ecosystems is also typically short. On the other hand,

BGD
12, 2491–2532, 2015

these upland forested ecosystems are also characterized by greater surface roughness and vegetation stabilization of topsoil, compared to agricultural or heavily logged hillslopes. Consequently, it is important to understand the dynamics of eroded C and N erosion in such systems for our larger understanding of the role of erosion in terrestrial carbon sequestration because sediment exported from such small, minimally disturbed low-order catchments can experience significant C oxidation during transport (Berhe, 2012). In agricultural systems, the oxidative C loss during erosion is assumed to be less than 20 % (Berhe et al., 2007). This same assumption cannot be justified for forested ecosystems because upland forest soils typically have higher concentration of OM in topsoil (as litter or OM rich mineral topsoil) and selective surface erosion processes in forests mobilize OM-rich sediment, compared to cultivated or grazing systems, or erosion.

We quantified the mass and composition of sediments exported from eight low-order catchments to determine the effect of soil erosion on the C and N cycling in upland forest ecosystems. To infer how changes in precipitation (i.e., snow–rain balance and runoff timing) can impact amount, nature, and fate of eroded OM, we compared findings from two sets of four minimally disturbed forested catchments in the southern part of the Sierra Nevada. The studied catchments are located at two contrasting elevation zones where the higher elevation catchments receive majority of their precipitation as snow and the lower elevation catchments receive half of their precipitation as snow and the rest as rain (Eagan et al., 2007; Hunsaker and Neary, 2012). Specifically, this work addresses two critical questions: (a) how rates of sediment yield are related to interannual differences in precipitation; and (b) is the biochemical composition of eroded sediments better correlated to catchment characteristics (like soil properties and slope geometry) or climate (i.e precipitation).

2 Site description and methods

2.1 Site description

This study was conducted within the US Forest Service Kings River Experimental Watershed, located in the Sierra National Forest (37.012° N, 119.117° W; Fig. 1). We used eight low-order catchments (ranging from 48 to 227 ha in size), grouped within two elevation zones as the Providence and Bull catchments (Fig. 2). The Providence catchments (1485–2115 m in elevation) receive approximately half of their precipitation as rain. Approximately 15 km to the southeast, the higher-elevation Bull catchments (2050–2490 m) receive the majority (75–90 %) of precipitation as snow (Hunsaker and Neary, 2012). Both elevation groups experience a Mediterranean-type climate with the majority of precipitation (rain or snow) falling in the winter. The lower-elevation Providence catchments are also being investigated as part of the Southern Sierra Critical Zone Observatory (CZO, www.criticalzone.org/sierra) project. Mean (± SD) annual air temperature for water years 2004–2007 was 11.3 ± 0.8 °C and 7.8 ± 1.4 °C at the low and high elevation sites, respectively (Johnson et al., 2011). Annual precipitation during the years of this study (water years 2005–2011) was similar across elevations but varied more than two fold among years (750–2200 mm, Fig. 3, see Hunsaker and Neary (2012) and Climate and Hydrology Database Projects (CLIMDB/HYDRODB), www.fsl.orst.edu/climhy). An important difference between the two catchment groups in Providence and Bull is that 75 to 90 % of the precipitation in Bull is delivered as snow, compared to only 35 to 60 % in Providence (Johnson et al., 2011).

The catchments have experienced minimal logging and virtually no fire activity over the past century (US Forest Service Pacific Southwest Research Station, unpublished data, M. Steumky and C. Hunsaker, 2012). In KREW, the Providence and Bull watersheds have been under long-term fire suppression for 65–80 years, with no documented fires over 10 acres in the last 110 years. The primary source of disturbance in these catchments is human activity on US Forest Service roads.

BGD
12, 2491–2532, 2015

Soil in the study area is derived from granite and granodiorite bedrock, and is dominated by the Shaver, Cagwin, and Gerle-Cagwin soil series. The Shaver series is most prominent (48–66 % coverage) in three of low elevation Providence catchments, while the higher elevation Bull catchments are dominated by the Cagwin series (67–98 % coverage) (Johnson et al., 2011). The Shaver series is in the US Department of Agriculture Soil Taxonomic family of coarse-loamy, mixed mesic Pachic Xerumbrepts. The Cagwin series is in the mixed, frigid Dystric Xeropsamments family. The Gerle series is in the coarse-loamy, mixed, frigid Typic Xerumbrepts family. See Johnson et al. (2011) for more detailed information on chemical and physical variation of soil in the study catchments. The dominant aspects of these catchments is southwest (Bales et al., 2011).

From 76 to 99 % of the vegetation cover in the Providence catchments is Sierra mixed conifer, the rest consisting of chaparral and land with no vegetation cover. By comparison, in the Bull catchments, less than 78 % of the vegetation cover is Sierra mixed conifer, with 19–43 % red fir (Bales et al., 2011; Eagan et al., 2007; Johnson et al., 2011, 2012). The Sierra mixed-conifer cover includes about 1/3 each of pines, incense cedar, and fir species (Johnson et al., 2011) where the specific species consist of: white fir (*Abies concolor*), ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*Pinus jeffreyi*), black oak (*Quercus kelloggii*), sugar pine (*Pinus lambertiana*), and incense cedar (*Calocedrus decurrens)* (Bales et al., 2011).

Using a multi-year record of annual sediment export, along with data on C and N concentration of eroded sediments, we quantified interannual and spatial variation in sediment export and composition, along with total C and N export from the catchments. Soils from different hillslope positions in our study catchments were compared to exported sediment to evaluate the impact of lateral transport of topsoil on OM amount and composition. We characterized newly collected sediment samples from the catchments for water years 2009–2011 (Table 1) and archived sediment samples from water years 2005, 2007, and 2008 (Eagan et al., 2007; Hunsaker and Neary, 2012) that were collected and archived by the US Forest Service Pacific Southwest

BGD
12, 2491–2532, 2015

Research Station in Fresno, CA (stored air-dry, at room temperature in the dark). There were no archived sediments preserved from water year 2006.

Sediment samples were compared to soil samples collected from 18 sampling points along representative transects for each group of catchments (see Fig. 1). Each of the transects were laid out along hillslope toposequences and we sampled at the crest, backslope, and foot/toe-slope (hereafter characterized as "depositional") landform positions. *Crest* samples were taken at the top of a ridgeline, where the slope was $< 5^{\circ}$. *Backslope* samples were taken where the slope change was constant (slopes between 5 and 25°). *Depositional* samples were taken in areas where slopes were converging and curvature was minimal (i.e., below the footslope and as close to flat as possible). These depositional areas are small (typically less than 10 m in length), as the catchments are steep and have minimal flat surfaces near the creeks and drainages. To quantify slope at each sampling point, Spatial Analyst tools from the ArcGIS software ArcMap 10.0 (ESRI, Redlands, CA, USA) were used to calculate slope from a 10 m Digital Elevation Model (DEM). Soil samples from each of hillslope position were collected in August and September, 2011, using a hand auger with a 5 cm diameter bucket. Depths were separated into five layers: organic horizon, 0–10, 10–20, 20–40, and 40–80 cm. Soil samples were kept in a cooler on ice packs until returned to the laboratory, where they were transferred to a refrigerator and kept at 4 °C until processing within three months. Soil sampling locations were selected to minimize variation in aspect and slope, factors that might influence overland transport and the energy of incoming precipitation. Soil across the catchments was previously characterized (Johnson et al., 2011, 2012), providing a larger data set against which to compare the results of this study.

Sediment from each catchment was captured in basins that allow sediment particles to settle as stream water slows passing through the basin (Eagan et al., 2007). Constructed to fit the topography, basin dimensions vary in size but are roughly 2–3 m wide by 8–15 m long. Annual sediment loads were quantified at the end of the water year (WY; 1 October of the previous year through 30 September) in August

BGD
12, 2491–2532, 2015
Soil carbon and nitrogen erosion in forested catchments in the Sierra Nevada
E. Stacy et al.

and September, when water flows were lowest. For collection, streams were diverted underneath the basin lining for several days while excess water drained. Material in the sediment basins was emptied using buckets and shovels and weighed in the field using a hanging spring scale (capacity of 50 ± 0.5 kg). A representative sample (~ 20 kg) was returned to the US Forest Service Pacific Southwest Research Station Fresno office. Subsamples (~ 2 kg) were transported in a cooler to UC Merced and stored at 4 °C until further processing.

2.2 Physical characterization of soil and sediment

Soil and sediment (air-dry, < 2 mm sieved samples) pH was measured in 1 : 2 (w / w) soil to water suspension using a combination electrode (Fisher Scientific Accumet Basic AB15 meter, Waltham, Massachusetts). Organic matter was removed from the soil and sediment samples to permit physical and mineralogical analysis of the mineral particles. Approximately 20 g of sample was mixed with 100 mL of sodium hypochlorite (6 % NaOCl, adjusted to pH 9.5 with 1 M HCl) for 30 min at 60 °C. Subsequently, solutions were centrifuged at 1500*g* for 15 min; thereafter, supernatant and floating organic particles were vacuumed. This process was repeated twice. After OM removal, 100 mL of deionized water was added to the sample, the suspension centrifuged, and the supernatant was aspirated and discarded. Samples were then dried at 40 °C, and analyzed for particle size distribution using laser diffraction and specific surface area using Brunauer Emmett Teller adsorption isotherms (Brunauer et al., 1938) at the Center for Environmental Physics and Mineralogy at the University of Arizona.

2.3 Characterization of C and N in sediment and soil

Total C and N were measured on the < 2 mm fraction following grinding (8000M Spex Mill, SPEX Sample Prep, Metuchen, NJ, USA) with a Costech ECS 4010 CHNSO Analyzer (Valencia, CA, USA). In the > 2 mm fraction, OM concentration was estimated by mass loss from ignition after 4 h of combustion at 440 °C in a muffle furnace. All

BGD
12, 2491–2532, 2015

values have been corrected to oven-dry (105°) sample weight and are reported as the mean of three analytical replicates ± standard error, except where noted.

2.4 Data analysis

Data are presented as mean ± standard error ($N = 3$), except where noted. Explanatory factors for C and N concentrations and the C : N ratio of sediment and soil were evaluated with a multivariate model to account for sampling year, catchment, sampling depth, and hillslope position. The strength of different model formats and interactions terms was evaluated using a stepwise regression run simultaneously in both directions, with the best model chosen according to the Akaike Information Criterion (Burnham and Anderson, 2002). The Tukey–Kramer HSD test ANOVA was used to test for significant differences between means of sediment mass, and C or N concentrations between sediment basins and collection years, and between hillslope position and transects for soils. For all statistical tests, an a priori α level of 0.05 was used to determine statistical significance. Statistical analyses were conducted using R 2.14.1 (http://www.r-project.org).

3 Results

3.1 Total sediment yield

Sediment yield in the eight catchments varied over several orders of magnitude. There were large differences among years and catchments (Table 1). Mean annual export across all catchments and years was $26.0 \pm 6.1\,\mathrm{kg\,ha^{-1}}$, but ranged from 0.4–177 $\mathrm{kg\,ha^{-1}}$. The lowest mean sediment export ($8.9 \pm 4.0\,\mathrm{kg\,ha^{-1}}$) was recorded for the P303 catchment. Particle size distribution in sediments exported from the catchments differed from the source soils, where sediments had higher concentration of sand and lower concentrations of sand and silt compared to soils. The mean pH and C

BGD
12, 2491–2532, 2015

concentration of sediments across the years was also lower at the high elevation Bull catchments (pH = 5.3. C = 5.4 %) compared to lower elevation Providence catchments (pH = 5.6. C = 8.5 %).

Sediment yield was positively correlated with total annual water yield (Fig. 2). Across samples from all catchments and years, there was a good correlation between water yield and sediment yield:

$$\log_{10}[S] = 1.87 \cdot \log_{10}[W] - 0.307$$
$$(R^2 = 0.62, \quad p < 0.0001, \quad n = 53) \tag{1}$$

where: S = annual sediment yield ($\mathrm{kg\,ha^{-1}\,yr^{-1}}$) and W = annual water yield ($1000\,\mathrm{m^3\,ha^{-1}\,yr^{-1}}$).

Among all measurements, four values were identified as outliers using the box-and-whisker plot method: the P304 catchment had very high export rates in 2005, 2006, and 2011 (177, 170, and 165 $\mathrm{kg\,ha^{-1}}$, respectively) relative to other water years and relative to sediment yield from other catchments in those years. The fourth outlier was T003 in 2005. Excluding these unusually high values improved the correlation between sediment yield and water yield to 0.64. The correlation between annual sediment export and annual water yield is stronger if P304 is separated from the other catchments (Eq. 2). Sediment yield from the P304 catchment is more sensitive to increases in water yield (Fig. 4).

When we analyze data from all catchments after excluding P304, the relationship between sediment yield and precipitation becomes stronger such that:

$$\log_{10}[S] = 1.67 \cdot \log_{10}[W] - 0.198$$
$$(R^2 = 0.72, \quad p < 0.0001, \quad n = 45)$$

Area-normalized sediment yield was highly variable across years, with the highest inter-year variability observed in catchments D102, B204, and T003.

3.2 Physical and chemical characteristics of sediment and soil

Sediments exported from all of the study catchments had higher sand concentration (average 69 % sand), and lower silt and sand concentrations, compared to topsoils in the source hillslope (average 49 % sand) (Tables 1 and 2). Soil texture classification was sandy-loam to loam and the particle size distribution was consistent across landform positions and soil depths (Table 2). Specific surface area was lower for sediment than for the soil where sediment in 2009 had the highest specific surface area ($3.3 \pm 1.0\,m^2\,g^{-1}$) compared to SSA of $8.5 \pm 1.7\,m^2\,g^{-1}$ for the transect in the higher elevation B204 bull catchment and $10.3 \pm 1.6\,m^2\,g^{-1}$ for transects in the lower elevation P303 providence catchment (Tables 1 and 2).

We observed important differences in soil properties between the two elevation groups. Soil pH varied with elevation, where the lower Providence catchments had a higher pH values compared to the slightly more acidic soils in the upper Bull catchments ($p < 0.0001$; Table 2). We found no difference in soil pH among soil depths within high or low elevation catchments. Sediment (WY 2009–2011) had significantly lower pH than the soils ($p = 0.01$). Sediment from the lower catchments was also more acidic than the material from the upper catchments, but the range between the means was smaller than the difference in the soil.

3.3 C and N concentrations in sediment and soil

The material that was collected at the sediment basins at the end of each water year included variable amounts of undecomposed organic matter. Of the total mass of material in the sediment basins (considering all years and all basins), coarse woody debris (mostly as pinecones and conifer needles) comprised 4–20 % while about 1 % of the mass was accounted for by large woody debris that most likely fell at or near the basins from the surrounding trees. Fine organic matter of mixed origin accounted for 4–30 % of the total mass collected in the sediment basins. The total mass of sediment exported from the basins (all basins and years) ranged from 42 to 30 324 kg, which is equivalent to 0.4 to 177 kg ha^{-1} of the total area in the basins. The total export of particulate C from all the basins, and across all the years, ranged from 3 to 503 kg, with the exception of T003 that exported 2330 kg in 2005, which was equivalent to particulate C export of 0.025 to 4.2 kg ha^{-1} (T003, WY 2005 at 10.5 kg C ha^{-1}). In comparison, the total export of particulate N for all years and basins was between 0.14 and 21 kg, with the exception of T003 that exported 88.7 kg in 2005, which was equivalent to between 0.001 and 0.2 kg N export per hectare land area of the basins (T003, WY 2005 at 0.4 kg N ha^{-1}).

Sediment yield across both catchments and years was much more variable, as shown by coefficients of variation, than the sediment composition (Table 3). For any given year, sediment yield across the catchments was more consistent than the interannual variation, but C and N concentrations, and the C : N ratio in the sediments showed similar variation whether compared across space or time. While sediment composition was less variable than sediment yield overall, C and N concentrations still showed statistically significant interannual and interbasin variation (Fig. 3). In the sediment samples we analyzed, C concentrations ranged from 15.5 to 190 g kg^{-1}, and N from 0.50 to 7.10 g kg^{-1}. In a multivariate model with water year and source catchment as the explanatory factors, both year ($p < 0.001$) and source catchment ($p < 0.01$) significantly influenced C and N concentrations ($n = 46$). Interactions between catchment and year could not be evaluated because there were too few replicates. However, classifying the catchments into groups by elevation was not significant for explaining either sediment C concentrations or N concentrations. Grouped by year, sediment from WY 2007–2009 had significantly higher mean C concentrations than sediment from WY 2011 (Fig. 3a and b). Sediment N concentrations in WY 2007–2009 were also significantly higher than WY 2005 and 2010 (Fig. 5c). Sediment yield was inversely correlated with C and N concentrations ($R^2 = 0.26$ and 0.19, respectively; $p < 0.01$, $n = 46$). Catchment averages showed fewer significant differences in mean sediment C concentrations than annual averages (Fig. 5b). The disparities did not correspond to elevation, as two of the three catchments with low C concentrations were

BGD
12, 2491–2532, 2015

in the higher elevation drainages, while the third was in the low elevation drainage group. Mean N concentrations were more consistent than C concentrations across catchments (Fig. 5d). For seven catchments, the C : N ratio ranged from 20.4 to 36.8, with a mean of 27.1 (Fig. 5f). The only significant difference was found in the upper elevation catchment, B201, which had comparatively higher N concentrations. The C : N ratios in B201 sediment are the lowest in each year (Fig. 5e).

The best predictive model for C and N concentrations in soils included landform position, depth and transect, as well as an interaction between transect and landform position ($R^2 = 0.883$; $p < 0.0001$, $n = 47$). Other variables evaluated but not included in the final model were the source catchment and interactions between the variables. Mineral soils had similar C and N concentrations and C : N ratios at both sampling sites. The low elevation Providence catchment had a wider range in C concentrations (9.0–98 $\mathrm{g\,kg^{-1}}$) in the surface soil (0–10 cm), than the Bull catchment soils (18.0–63.0 $\mathrm{g\,kg^{-1}}$, except for one depositional point that had a C concentration of 167 $\mathrm{g\,kg^{-1}}$). The N concentrations in soil ranged from 0.5 to 3.5 $\mathrm{g\,kg^{-1}}$ in Providence, and 1.0 to 5.1 $\mathrm{g\,kg^{-1}}$ in Bull. Differences between the elevation groups were not statistically significant for either C or N concentrations.

The largest differences were between the organic horizon and the mineral soils. Carbon to nitrogen ratio was statistically higher in the organic horizon than the mineral soils (means 51 ± 3.9 and 25 ± 0.9 %, respectively, $p < 0.0001$). There was no difference in either the C or N concentration, or the C : N ratio of the organic horizon between landform positions, transects, or catchments (data not shown). Depositional hillslope positions had significantly higher C and N concentrations than both the crest and backslope positions, which were similar (Table 2). The highest variability in C and N concentrations was also observed in the samples from depositional locations. Sediment C concentrations in water years 2005, 2010, and 2011 were similar to the soil range, but in the other years, sediment C concentrations were much higher than soils. For N, differences between each sediment year and the soil were even more pronounced.

BGD
12, 2491–2532, 2015

3.4 C and N enrichment ratios

Enrichment ratios of C and N (ER, the ratio of C or N concentration in the eroded sediment divided by their concentration in source soil in hillslopes) were highest during years with low precipitation and lowest during high precipitation years, suggesting lower selectivity of erosion during wet years where precipitation provides enough energy to laterally transport large amounts of material. In contrast, during years of low precipitation, we observe selective transport of fine, organic matter mainly from the forest floor or litter. Furthermore, calculated enrichment ratios were considerably different in samples from the high elevation Bull catchments depending on whether we assumed the eroded sediment was derived from the crest, backslope or the depositional positions. However, the same was not true for the low elevation catchments, where the only difference in ER across hillslope positions for both C and N was observed among years (Fig. 6). For the Providence catchments, highest ER was for water year 2009, while in the Bull catchments it was 2007.

4 Discussion

Our analyses of sediment transport rates from the KREW catchments and their composition showed strong influence of climate on soil erosion rate in the southern Sierra Nevada. In agreement with our hypothesis that sediment yield is closely related to interannual differences in precipitation, we found that annual discharge, a proxy for precipitation, was strongly and positively correlated to total annual sediment yield, more than watershed size, slope and other geomorphic or soil characteristics. The range and magnitude of exported sediment was comparable to total sediment transport rates in water years 2001–2009 from a subset of these catchments (Eagan et al., 2007; Hunsaker and Neary, 2012). A comparison of area-normalized annual sediment yield and water yield highlighted the extreme sediment yield response in some years.

BGD
12, 2491–2532, 2015

We hypothesized that sediment biochemical composition is better correlated with catchment characteristics such as soil composition and slope geometry. We found small changes in C and N concentrations in sediments across the water years. Assuming a rough bulk density for the sediment of 1.5 $g\,cm^{-3}$, the average annual sediment yield resulted in the export of 0.2–4.4 $kg\,C\,ha^{-1}\,year^{-1}$. In comparison, the stock of C in these soils was previously estimated to be between 80 000 and 111 000 $kg\,C\,ha^{-1}$ (Johnson et al., 2011). Results from WY 2005–2011 supported the hypothesized influence of water year (i.e. climate) on sediment transport of fine organic and mineral matter. However, we reject our hypothesis on the drivers of sediment composition. Sediment composition was far more consistent than sediment yield across catchments as well as years. Furthermore, there was no generalizable difference in composition of the eroded sediment in the lower vs. higher elevation catchments. With relatively consistent C and N concentrations, these results suggest that the total amount of OM exported from the Sierra Nevada largely depends on total sediment and water yield.

Forested upland catchments are characterized by surface roughness and spatial variability in amount of sediment transported by erosion and nature of the eroded topsoil material. It is likely that the spatial variability of erosion across the catchments drives the observed disagreement in the rates of water vs. sediment yield. This is especially true in catchments that have not experienced major perturbations due to agriculture, clear-cutting or fire wildfires, such as the catchments we studied in the southern Sierra Nevada that have not experienced major perturbation for over a century. Significant spatial variability of source and nature of eroded topsoil material has previously been observed in other ecosystems. For example, Stafford (2011) notes that small differences in surface cover or connectivity may contribute to exceptionally high or varied sensitivity in sediment transport from eroding catchments, particularly when high sediment yields are observed from roads and native surfaces (without gravel or paving) (Stafford, 2011). Climate plays important role in generating sediment along the road segments, especially during high precipitation years when erosion processes can generate and transport large amount of sediment (MacDonald et al., 2001)

On the vegetated hillslopes in our study catchments, mean erosion rates measured using sediment fences (3.8–7.9 kg ha^{-1} year^{-1}; Stafford, 2011) were comparable in magnitude to total sediment export we found in this work. Previously, it was shown that water-driven surface erosion from or near roads in the southern Sierra catchments is orders of magnitude higher than erosion on vegetated hillslopes (Stafford, 2011) owing to the distance of the road to streams or connectively between roads and streams (Luce and Black, 2001; MacDonald and Coe, 2008; Croke et al., 2005; Ketcheson and Megahan, 1996). In the Providence and Bull catchments, there are relatively few erosional features (gullies, mass wasting or bank erosion) that contribute to high sediment export by connecting roads or streams, as is typically observed in other semi-arid catchments (Nadeu et al., 2012). The disparity between rates of road sediment production and the yield of sediment from these relatively undisturbed catchments is likely due to a combination of the low areal extent of the roads and the lack of connectivity between the roads and the streams.

The high sediment yield from catchment P304 remains unexplained. The catchment also had abnormally high sediment yield in WY 2003 (158 kg ha^{-1}; Eagan et al., 2007) that was comparable to high sediment yield years shown here for 2005, 2006, and 2011. The P304 catchment has steep slopes adjacent to the stream. However, a bank erosion survey conducted in 2005 showed catchment P304 had high erosion at one point in the stream headcut, but overall bank and headcut erosion was much smaller than the other three catchments in the Providence Creek basin (Martin, 2009), discounting stream erosion as a possible source. Hunsaker and Neary (2012) attributed the anomaly to the high fraction of core stones in the P304 catchment. Other possibilities to explore might include whether road density and availability of road running parallel to the stream could be contributing factors.

Hillslope gradient, especially in areas adjacent to streams, may play a prominent role in sediment yield (Litschert and MacDonald, 2009). We found no significant difference

BGD
12, 2491–2532, 2015

in sediment yield between the two elevation groups. Slope and other characteristics of catchment geometry were independent of elevation-associated climate differences. The three catchments with the highest sediment yields (T003, P304 and D102) had steep (frequently greater than 25°) slopes near the stream, while other catchments have more moderate (< 15°) slopes in those areas (Fig. 7). The steepest slopes adjacent to the stream in catchment D102 are made up of exposed bedrock, not soil, which may explain why mean annual sediment export in this catchment was only slightly higher than in catchments B201 and B203. The high sediment yield relative to water yield found in T003 was not anticipated because this catchment has never been impacted by roads or logging (Hunsaker and Neary, 2012). Potentially, the long, narrow geometries of T003 and P304 may have contributed to higher sediment export because transport distance to streams was reduced (Hunsaker and Neary, 2012).

We observed an inverse correlation between C and N concentrations and sediment export. The negative correlation between sediment yield and OM composition can be explained in three ways: preferential transport, differences in the source of the material, or sampling basin capture efficiency. First, higher C and N concentrations could result from preferential transport of OM through surface erosion in drier years. Enrichment was most notable in WY 2009 and 2010, when sediment from the lower elevation catchments had C and N concentrations as much as three times higher than the soils studied here (Fig. 6). In those years, sediment concentrations fall between values for the mineral soil and the organic horizon. Water-based surface erosion processes (sheet erosion) preferentially mobilize organic-rich surface material over mineral soils from deeper in the soil profile (Nadeu et al., 2012).

Second, intense storms or high stream and gully flows may detach and transport material from stream banks deeper in the soil profile. This mineral material low in C and N would thereby decrease or dilute concentrations of captured sediment. Farther north in the Sierra Nevada, streambed and streambank erosion were found to be significant sources of sediment flowing into Lake Tahoe (Coats, 2004; Nolan and Hill, 1991). However, Martin (2009) found that stream bank erosion did not

BGD
12, 2491–2532, 2015

explain erosion rates in the Providence catchments. The catchments in the study have some geomorphic features which increase connectivity in the catchments (e.g., gullies or convex hillslopes) (Stafford, 2011), though these features are infrequent. This explanation is even less likely because the dominating surface erosion processes in the catchment would not reach OM-poor material deep in the profiles since the A horizon has a mean depth of 25 ± 1.5 cm ($n = 84$; Dahlgren et al., 1997; Johnson et al., 2012) and C and N concentrations decline gradually across the depths examined here.

Third, enrichment of C and N in sediments during low flow years may be due to more efficient capture of sediment in the settling basins. During high flow years, small mineral particles and light organic particles could potentially remain in suspension through the entire basin, while coarser and heavier particles settle. Such a process is supported by the coarsening texture of mineral particles and decreasing specific surface area in the order: soil < WY 2009 sediment < WY 2010 sediment < WY 2011 sediment (with increasingly higher flows for those same water years).

4.1 Sediment and SOM erosion in rain vs. snow dominated forested catchments

One of the main questions in this study was the influence of precipitation form and amount on sediment transport. A shift in precipitation from snow to rain, under anticipated climate change scenarios can have important implications for sediment transport. Rainstorms could contribute to export of sediment through raindrop impact and overland transport. In the lower catchments, a greater fraction of precipitation falls as rain than in the higher elevation catchments, and those precipitation events lead to stream discharge more quickly (Hunsaker et al., 2012). Snowmelt in the higher elevation systems, or under colder climate scenarios is likely to have less influence on erosion (than rain events) since snowmelt occurs more gradually, allowing for higher rates of infiltration of laterally moving water in the catchments. Our comparison of the low and high elevation group of catchments did not reveal statistically significant differences in the means of annual sediment yield or sediment composition. However, it is possible that the low and high elevation catchments can exhibit differences in

BGD
12, 2491–2532, 2015

sediment yield or composition in the event of disturbances such as fire or thinning due if these activities lead to disturbance of the forest floor.

The interannual variability of sediment OM composition observed for any one catchment further suggests differences in erosion type or the source of the sediment. Sediment composition was influenced more by amount of precipitation than by the source catchment characteristics. Source catchment was a significant factor in predicting the sediment composition, but not the dominant one. Carbon-to-nitrogen ratios were consistent across years. Lower C : N ratios in B201 sediment might be due to the prevalence of meadow vegetation at the edge of the stream while the other streambanks are dominated by forest vegetation, or changes in capture efficiency of the sediment basins for years with different precipitation amounts or intensities.

Using results from this study to determine possible sources of sediment in these catchments, we found data that suggests that the eroded sediment is likely mostly a mix of inputs from the depositional and backslope areas. Using only C and N concentrations and the C : N ratio as indices, we find that sediment values fell partway between crest and backslope values on one side, and values from depositional hillslope positions on the other (Fig. 5, Tables 2 and 3). Observed sediment composition could also be explained through input from backslopes with concurrent enrichment of light organic particles. Sediment and depositional locations were expected to have high C and N concentrations partially due to the expected preferential transport of light organics and reduced decomposition under less oxic conditions (Berhe et al., 2012a). However, some depositional locations had even higher C and N concentrations than the sediments suggesting that depositional locations can likely effectively store free, light OM at depth (Berhe et al., 2012a), in addition to in situ OM contributions from net primary productivity. However, the lower specific surface area found in the two depositional landform positions suggest strong likelihood for deposition of coarse material while the finer particles are transported further (Nadeu et al., 2011). Depositional and crest positions cover a very small part of each catchment when compared to the areal extent of the backslope, where many of the slopes adjacent to

BGD
12, 2491–2532, 2015

these streams have steep slopes (> 25°; Fig. 7), suggesting that the backslope position are likely important contributors of sediments that are exported from the watersheds.

Overall, our findings show that there was no consistent statistically significant different erosion rates of sediment, C or N from rain vs. snow dominated headwater catchments in the southern Sierra Nevada. However, we found differences in enrichment ratios of C and N in eroding sediments that are likely driven by higher rates of sediment mobilization during wetter years that is driven by availability of erosive energy to laterally mobilize more mass from the hillslopes. We also found that annual discharge is a good predictor of sediment yield in both the snow and rain dominated catchments. The findings that: (a) sediment was coarser than source soils, suggesting preferential transport of this material or preferential collection, and (b) most of the collected sediments materials appear to be enriched in litter suggests that it is likely derived from surficial sources and that are likely transported by sheet erosion as the dominant erosional process.

4.2 Thoughts on the sediment basin approach and use of annually aggregated data

Despite a strong relationship between water yield and sediment yield (Fig. 2), we found that the range of sediment yield was as much as an order of magnitude greater than the difference in flow for any given year. This difference suggests a missing factor that is likely important in influencing sediment yield across years. One possibility is that using annual water yield values calculated from mean monthly flow rates minimizes the contribution of high discharge rates at shorter time-scales. Intense precipitation events can mobilize large amounts of sediment. At the KREW catchments, an especially intense rainstorm (290 mm over 30 h, with 27 mm h^{-1} peak intensity) in WY 2003 occurred the same year that five of the catchments had high sediment yield (Eagan et al., 2007). Even though we recognize the contribution of the intense rain events, the use of data derived from annually aggregated sediment basin approach, does not allow ascertaining the timing of sediment transport into the trap basins.

Moreover, the capture efficiency of settling basins depends on prevailing precipitation regimes, characteristics of the sediment in suspension, and of the basins (e.g., the geometry of the basin). In a review of several studies, Verstraeten and Poesen (2000) found trapping efficiency rates of sediment mass in individual events can be as low as 50 %, especially in high discharge events. Most of the time, discharge in the streams in the southern Sierra Nevada is low, with high discharge limited to discrete events. During low discharge events in either the low or high elevation catchments, the residence time of water in the catchments is longer and trapping efficiency of the basins is expected to be higher. Furthermore, low discharge events are also expected to lead to low sediment delivery to basins that are located at the mouth of the catchments. Hence, low capture rates may explain the lower C and N concentrations during years with high discharge, likely caused by low capture efficiency of fine, light and lower density particles, especially undecomposed free OM and very fine mineral particles. This is corroborated by the coarsening of particles from soil to sediment. If this assumption is valid then total material exported from the catchments is likely to have had more OM than what was captured in the basin – where the low C and N capture efficiency in the basins would be attributed to local deposition of particulate C and N within the catchment (Berhe et al., 2007, 2008, 2015), sorption of laterally flowing dissolved OM due to sorption by soil minerals (Sanderman and Amundson, 2008; Sanderman et al., 2008, 2009). The issue of low capture efficiency during high intensity rain events is less likely to be an important issue in the higher elevation catchments, where most of the discharge is driven by spring snowmelt that proceeds at a much slower pace downstream.

4.3 Implications for predicting fate of eroded OM in upland forest ecosystems

The process of SOM erosion in upland forest ecosystems and its contribution to the erosion-induced C sink are fundamentally different than those in cultivated and grassland ecosystems that are more commonly studied to examine the role of erosion on the global carbon cycle. First, the rate of SOM erosion can be considerably higher in

BGD
12, 2491–2532, 2015

forested upland ecosystems because the landscape tends to have steeper slopes, and depending on the nature of the aboveground vegetation they also tend to have a litter layer (O-horizons) and higher concentration of C and N in topsoils (Dahlgren et al., 1997; Johnson et al., 1997) compared to agricultural systems (Quine and Van Oost, 2007; Van Oost et al., 2007; Berhe et al., 2007; VandenBygaart et al., 2015). Second, unlike in cultivated or grassland systems, a larger fraction of the eroded SOM is likely to be decomposed during or after deposition since most of the eroded SOM is in the form of litter or free light fraction OM that is not protected by physical or chemical association with soil minerals. Our results agree with the above statements in that we found that the eroded sediments were enriched in organic-rich topsoil and litter in the minimally disturbed, upland forest ecosystems in the southern Sierra Nevada. Large amount of litter at different stages of decomposition (O-horizon) was laterally mobilized down the steep slopes. Moreover, in some cases we found that the travel distance of topsoil material from source slopes to streams was very short with $> 25\%$ slope allowing for very little processing or burial in downslope depositional settings of the eroded organic-rich topsoil before it enters aquatic systems. By comparison, a larger fraction of the OM eroded from less steep slopped hillslopes in cultivated systems is likely to be stabilized by burial in downslope depositional landform positions (VandenBygaart et al., 2012, 2015). In the forested hillslopes we studied in KREW, eroded litter was deposited in riparian areas that are characterized by being poorly drained and/or under snow cover for most of the year limiting rates of aerobic decomposition of organic substrates while maintaining high potential for dissolved losses of OM or anaerobic decomposition of substrates during the wet season (Berhe and Kleber, 2013). Our results show that several kilograms of C may be exported from a hectare each year. While C and N concentrations vary from year to year, the variability in C and N concentrations and C : N ratio of eroded sediments was more consistent than the total sediment exported.

The net impact of erosion on the C cycle in these forested catchments is ultimately a balance between the rate of OM replacement in the eroding slopes by production of new photosynthate, and rate of decomposition of eroded OM during transport or

BGD
12, 2491–2532, 2015

after they are deposited in downslope depositional landform positions (Berhe et al., 2007). In all of our study watersheds, the potential for replacement of eroded SOM by photosynthesis is high, but the potential for gaseous and dissolved loss of eroded OM-rich material during transport or after it arrives in the riparian areas is also high – reducing the likelihood that erosion can constitute a significant sink of atmospheric CO_2 in such forested upland temperate ecosystems. Furthermore, anticipated changes in amount and distribution of precipitation and changes in temperature due to anticipated climate change are expected to have significant effect of forest productivity, soil organic matter decomposition, and erosional distribution of topsoil and associated SOM (Berhe et al., 2012b, 2014; Berhe and Kleber, 2013). Based on the results we presented above, it is plausible to conclude that changes in climate will have important implications for both the nature and amount of OM that is eroded from forested ecosystems. We found that during years with low precipitation sediment eroded from upland temperate forest ecosystems had higher proportion of light carbonations materials and hence high concentrations of C and N. On the other hand, years with high precipitation had relatively higher proportion of mineral particles because the higher erosivity of rainfall (energy to mobilize large mass) enabled erosion of minerals and mineral-associated OM in addition to the free light OM constituents. Even though we did not explicitly address this in this work, similarly higher rates of lateral mobilization of minerals and mineral-associated OM would also be expected for years with large number of intensive rain events. Hence, the fate of the C and N eroded from such catchments and its contribution towards erosion-induced C sequestration will depend on how far the material is transported and in what type of depositional environments that it is ultimately deposited.

5 Conclusions

Findings of this study demonstrate that the amount and nature of SOM eroded from forested upland catchments is fundamentally different than that in cultivated and

BGD
12, 2491–2532, 2015

grassland systems that are more commonly studied to determine the role of soil erosion on terrestrial carbon sequestration. We found that the sediments eroded from our study catchments were OM rich, with a potential for significant gaseous and dissolved loss of OM during transport or after depositional in downslope or downstream depositional landform positions. Our results suggest that variability in climate, represented by stream discharge, is a primary factor controlling the magnitude of C and N eroded from upland temperature forest catchments. SOM erosion in forested temperate upland ecosystems is strongly controlled by climate and shifts in amount, distribution and intensity of precipitation events that are expected with anticipated climate change scenarios will likely have important implications for changing the amount and nature of SOM eroded from such catchments. Furthermore, forest management practices that disturb the land surface or change the density of vegetation cover are expected to have similar effects.

Acknowledgements. This research was conducted in the Kings River Experimental Watershed (KREW), which was established and is managed for US Forest Service Pacific Research Station. KREW was set up using funds from the National Fire Plan of the USDA Forest Service. Additional funding for this work was provided from the US Forest Service, the Southern Sierra Critical Zone Observatory Project from the National Science Foundation (EAR-0725097) and a Graduate Research Council grant from the University of California, Merced. We thank Matthew McClintock; members of the Berhe and Hart labs at UC Merced; researchers within the Southern Sierra Critical Zone Observatory (SSCZO), and the US Forest Service crews from the Pacific Southwest Research Station for assistance in the field and in lab portions of this work.

References

Anderson, C. J. and Lockaby, B. G.: Research gaps related to forest management and stream sediment in the United States, Environ. Manage., 47, 303–313, doi:10.1007/s00267-010-9604-1, 2011.

Bales, R. C., Hopmans, J. W., O'Geen, A. T., Meadows, M., Hartsough, P. C., Kirchner, P., Hunsaker, C. T., and Beaudette, D.: Soil moisture response to snowmelt and rainfall in a Sierra Nevada mixed-conifer forest, Vadose Zone J., 10, 786–799, doi:10.2136/vzj2011.0001, 2011.

Berhe, A. A.: Decomposition of organic substrates at eroding vs depositional landform positions, Plant Soil, 350, 261–280, doi:10.1007/s11104-011-0902-z, 2012.

Berhe, A. A. and Kleber, M.: Erosion, deposition, and the persistence of soil organic matter: mechanistic considerations and problems with terminology, Earth Surf. Proc. Land., 38, 908–912, doi:10.1002/esp.3408, 2013.

Berhe, A. A., Harte, J., Harden, J. W., and Torn, M. S.: The significance of erosion-induced terrestrial carbon sink, BioScience, 57, 337–346, 2007.

Berhe, A. A., Harden, J. W., Torn, M. S., and Harte, J.: Linking soil organic matter dynamics and erosion-induced terrestrial carbon sequestration at different landform positions, J. Geophys. Res., 113, G4, doi:10.1029/2008jg000751, 2008.

Berhe, A. A., Harden, J., Torn, M., Kleber, M., Burton, S., and Harte, J.: Persistence of soil organic matter in eroding vs. depositional landform positions, J. Geophys. Res., 117, G02019, doi:10.1029/2011JG001790, 2012a.

Berhe, A. A., Suttle, K. B., Burton, S. D., and Banfield, J. F.: Contingency in the direction and mechanics of soil organic matter responses to increased rainfall, Plant Soil, 358, 371–383, doi:10.1007/s11104-11012-11156-11100, 2012b.

Berhe, A. A., Arnold, C., Stacy, E., Lever, R., McCorkle, E., and Araya, S. N.: Soil erosion controls on biogeochemical cycling of carbon and nitrogen, Nature Education Knowledge, 5, 2 pp., 2014.

Berhe, A. A., Torn, M. S., and Harden, J. W.: Soil nitrogen storage and stabilization in eroding landscapes, in review, 2015.

Boix-Fayos, C., de Vente, J., Albaladejo, J., and Martínez-Mena, M.: Soil carbon erosion and stock as affected by land use changes at the catchment scale in Mediterranean ecosystems, Agr. Ecosyst. Environ., 133, 75–85, 2009.

Brunauer, S., Emmett, P. H., and Teller, E.: Adsorption of gases in multimolecular layers, J. Am. Chem. Soc., 60, 309–319, 1938.

Burnham, K. P. and Anderson, D. R.: Model Selection and Multimodel Inference: a Practical Information-Theoretic Approach, Springer-Verlag, New York, 2002.

Coats, R.: Nutrient and sediment transport in streams of the Lake Tahoe Basin: a 30-year retrospective, in: Proceedings of the Sierra Nevada Science Symposium: Science for Management and Conservation, 7–10 October 2002, Kings Beach, CA, General Technical Report PSW-GTR-193, USDA Forest Service, Pacific Southwest Research Station, Albany, CA, 143–147, 2004.

Croke, J., Mockler, S., Fogarty, P., and Takken, I.: Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity, Geomorphology, 68, 257–268, 2005.

Dahlgren, R., Boettinger, J., Huntington, G., and Amundson, R.: Soil development along an elevational transect in the western Sierra Nevada, California, Geoderma, 78, 207–236, 1997.

Eagan, S. M., Hunsaker, C. T., Dolanc, C. R., Lynch, M. E., and Johnson, C. R.: Discharge and sediment loads at the Kings River experimental forest in the Southern Sierra Nevada of California, in: Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18–22 October 2004, edited by: Furniss, M., Clifton, C., and Ronnenberg, K., US Department of Agriculture, Forest Service, Pacific Northwest Research Station, PNWGTR-689, Portland, OR, 2007.

Harden, J. W., Sharpe, J. M., Parton, W. J., Ojima, D. S., Fries, T. L., Huntington, T. G., and Dabney, S. M.: Dynamic replacement and loss of soil carbon on eroding cropland, Global Biogeochem. Cy., 13, 885–901, 1999.

Harden, J. W., Berhe, A. A., Torn, M., Harte, J., Liu, S., and Stallard, R. F.: Soil erosion: data say C sink, Science, 320, 178–179, doi:10.1126/science.320.5873.178, 2008.

Hunsaker, C. T. and Neary, D. G.: Sediment loads and erosion in forest headwater streams of the Sierra Nevada, California, in: Revisiting Experimental Catchment Studies in Forest Hydrology, Proceedings of a Workshop held during the XXV IUGG General Assembly in Melbourne, June–July 2011, IAHS Publ., Wallingford, UK, 353 pp., 2012.

Hunsaker, C. T., Whitaker, T. W., and Bales, R. C.: Snowmelt runoff and water yield along elevation and temperature gradients in California's southern Sierra Nevada, J. Am. Water Resour. Assoc., 48, 667–678, doi:10.1111/j.1752-1688.2012.00641.x, 2012.

IPCC: Climate change: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2007.

Johnson, D., Susfalk, R., and Dahlgren, R.: Nutrient fluxes in forests of the eastern Sierra Nevada mountains, United States of America, Global Biogeochem. Cy., 11, 673–681, 1997.

Johnson, D., Hunsaker, C., Glass, D., and Rau, B.: Carbon and nutrient contents in soils from the Kings River Experimental Watersheds, Sierra Nevada Mountains, California, Geoderma, 160, 490–502, 2011.

Johnson, D. W., Hunsaker, C. T., and Todd Jr., D. E.: Spatial variations in forest soils at two scales: comparisons of King's River Watersheds, California and Walker Branch Watershed, Tennessee, Biogeomon, 2012: The 7th International Symposium on Ecosystem Behavior, Northport, ME, USA, 15–20 July 2012, Theme 4, poster 27, 2012.

Ketcheson, G. L. and Megahan, W. F.: Sediment Production and Downslope Sediment Transport from Forest Roads in Granitic Watersheds, USDA Forest Service, Intermountain Research Station, INT-RP-486, Ogden, UT, 1996.

Kirkby, M. J.: Distance, time and scale in soil erosion processes, Earth Surf. Proc. Land., 35, 1621–1623, doi:10.1002/esp.2063, 2010.

Litschert, S. and MacDonald, L.: Frequency and characteristics of sediment delivery pathways from forest harvest units to streams, Forest Ecol. Manag., 259, 143–150, 2009.

Luce, C. H. and Black, T. A.: Spatial and temporal patterns in erosion from forest roads, in: Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas, American Geophysical Union, 165–178, 2001.

MacDonald, L. H. and Coe, D. B.: Road sediment production and delivery: processes and management, in: Proceedings of the First World Landslide Forum, International Programme on Landslides and International Strategy for Disaster Reduction, 18–21 November 2008, Tokyo, Japan, 381–384, 2008.

MacDonald, L. H., Sampson, R. W., and Anderson, D. M.: Runoff and road erosion at the plot and road segment scales, St. John, US Virgin Islands, Earth Surf. Proc. Land., 26, 251–272, 2001.

Martin, S. E.: Comparison of in-stream sediment sources and assessment of a bank migration model for headwater catchments in the Central Sierra Nevada, California, M.Sc. thesis, Environmental Systems, University of California, Merced, 2009.

Nadeu, E., de Vente, J., Martínez-Mena, M., and Boix-Fayos, C.: Exploring particle size distribution and organic carbon pools mobilized by different erosion processes at the catchment scale, J. Soil Sediment., 11, 667–678, 2011.

Nadeu, E., Berhe, A. A., de Vente, J., and Boix-Fayos, C.: Erosion, deposition and replacement of soil organic carbon in Mediterranean catchments: a geomorphological, isotopic and land use change approach, Biogeosciences, 9, 1099–1111, doi:10.5194/bg-9-1099-2012, 2012.

BGD
12, 2491–2532, 2015

Soil carbon and nitrogen erosion in forested catchments in the Sierra Nevada

E. Stacy et al.

Nolan, K. M. and Hill, B. R.: Suspended-sediment budgets for four drainage basins tributary to Lake Tahoe, California and Nevada, 1984–1987, US Department of the Interior, US Geological Survey, Sacramento, CA, 1991.

Parfitt, R. L., Baisden, W. T., Ross, C. W., and Rosser, B. J.: Influence of erosion and deposition on carbon and nitrogen accumulation in resampled steepland soils under pasture in New Zealand, Geoderma, 19, 154–159, 2013.

Quine, T. A. and Van Oost, K.: Quantifying carbon sequestration as a result of soil erosion and deposition: retrospective assessment using caesium-137 and carbon inventories, Glob. Change Biol., 13, 2610–2625, doi:10.1111/j.1365-2486.2007.01457.x, 2007.

Sanderman, J. and Amundson, R.: A comparative study of dissolved organic carbon transport and stabilization in California forest and grassland soils, Biogeochemistry, 89, 309–327, doi:10.1007/s10533-008-9221-8, 2008.

Sanderman, J. and Chappell, A.: Uncertainty in soil carbon accounting due to unrecognized soil erosion, Glob. Change Biol., 19, 264–272, 2013.

Sanderman, J., Baldock, J. A., and Amundson, R.: Dissolved organic carbon chemistry and dynamics in contrasting forest and grassland soils, Biogeochemistry, 89, 181–198, doi:10.1007/s10533-008-9211-x, 2008.

Sanderman, J., Lohse, K. A., Baldock, J. A., and Amundson, R.: Linking soils and streams: sources and chemistry of dissolved organic matter in a small coastal watershed, Water Resour. Res., 45, W03418, doi:10.1029/2008WR006977, 2009.

Stafford, A. K.: Sediment production and delivery from hillslopes and forest roads in the Southern Sierra Nevada, California, M.Sc. thesis, Department of Forest, Rangeland, and Watershed Stewardship, Colorado State University, Fort Collins, CO, 197 pp., 2011.

Stallard, R.: Terrestrial sedimentation and the carbon cycle: coupling weathering and erosion to carbon burial, Global Biogeochem. Cy., 12, 231–257, 1998.

Van Oost, K., Quine, T., Govers, G., De Gryze, S., Six, J., Harden, J., Ritchie, J., McCarty, G., Heckrath, G., and Kosmas, C.: The impact of agricultural soil erosion on the global carbon cycle, Science, 318, 626–629, 2007.

VandenBygaart, A., Kroetsch, D., Gregorich, E. G., and Lobb, D.: Soil C erosion and burial in cropland, Glob. Change Biol., 18, 1441–1452, doi:10.1111/j.1365-2486.2011.02604.x, 2012.

VandenBygaart, A. J., Gregorich, E. G., and Helgason, B. L.: Cropland C erosion and burial: is buried soil organic matter biodegradable?, Geoderma, 239–240, 240–249, doi:10.1016/j.geoderma.2014.10.011, 2015.

BGD
12, 2491–2532, 2015

Soil carbon and nitrogen erosion in forested catchments in the Sierra Nevada

E. Stacy et al.

Verstraeten, G. and Poesen, J.: Estimating trap efficiency of small reservoirs and ponds: methods and implications for the assessment of sediment yield, Prog. Phys. Geog., 24, 219–251, 2000.

Wang, Z., Govers, G., Oost, K. V., Clymans, W., den Putte, A. V., and Merckx, R.: Soil organic carbon mobilization by interrill erosion: insights from size fractions, J. Geophys. Res. Earth Surf., 118, 348–360, doi:10.1029/2012JF002430, 2013.

Yoo, K., Amundson, R., Heimsath, A., and Dietrich, W.: Erosion of upland hillslope soil organic carbon: coupling field measurements with a sediment transport model, Global Biogeochem. Cy., 19, GB3003, doi:10.1029/2004GB002271, 2005.

Table 1. Physical and biochemical characterization of the sediment material (< 2 mm), including pH_{water} (1 : 2 w/v), carbon (C) and nitrogen (N) concentrations, and particle size distribution (clay < 2 µ, silt 2–50 µ, and sand 50–2000 µm). Some samples were not measured due to lack of material (indicated by no data or nd).

Catchment and water year	pH_w^a	C ($g\,kg^{-1}$)[b]	N ($g\,kg^{-1}$)[c]	C : N ratio	Clay ($g\,kg^{-1}$)[d]	Silt ($g\,kg^{-1}$)[d]	Sand ($g\,kg^{-1}$)[d]	SSA ($m^2\,g^{-1}$)[d]
D102								
WY 2009	5.8[e]	146.1	6.5	22.5	nd	nd	nd	nd
WY 2010	5.9	55.1	1.9	29.7	69	247	685	1.53
WY 2011								
P301								
WY 2009	5.5	144.0	6.7	21.4	74	385	541	2.87
WY 2010	5.5	90.2	2.8	32.4	79	298	623	2.41
WY 2011	5.8	28.4	1.0	27.4	51	215	734	2.42
P303								
WY 2009	5.0	183.3	7.1	25.7	60	343	597	1.80
WY 2010	5.5	125.3	4.1	30.7	83	331	587	2.27
WY 2011	5.8	21.3	0.8	26.6	53	209	738	3.49
P304								
WY 2009	5.1	85.9	3.8	22.9	135	383	482	7.60
WY 2010	5.7	35.8	1.1	32.0	110	297	594	5.11
WY 2011	5.9	15.5	0.7	23.2	72	246	682	3.53
B201								
WY 2009	4.8	51.4	2.9	17.4	150	315	536	6.42
WY 2010	5.4	31.9	1.4	22.0	123	289	588	5.07
WY 2011	5.4	23.5	1.3	18.0	112	287	602	3.65
B203								
WY 2009	4.7	58.4	2.2	26.8	58	245	698	1.05
WY 2010	5.5	16.4	0.5	32.5	69	198	734	1.77
WY 2011	5.4	27.5	0.9	29.3	56	212	732	1.13
B204								
WY 2009	5.0	64.3	2.5	25.3	58	233	709	1.99
WY 2010	5.4	24.7	0.70	36.7	70	246	685	2.18
WY 2011	5.3	48.6	1.4	33.8	69	246	685	2.28
T003								
WY 2009	5.4	107.8	4.4	24.6	53	322	625	1.51
WY 2010	5.6	78.1	2.3	34.6	68	304	629	1.99
WY 2011	5.5	119.5	4.3	27.6	76	339	585	2.46

[a] Standard error ≤ 0.06 for replicates. [b] Standard error ≤ 0.03 for analytical ($n \geq 3$) replicates. [c] Standard error ≤ 0.8 for analytical ($n \geq 3$) replicates. [d] $n = 3$ analytical replicates. [e] Due to the limited mass of archived material, the pH value for D102 from WY2009 is given from a previous analysis as pH_{water} with 1 : 2.5 soil weight to water volume.

BGD

12, 2491–2532, 2015

Table 2. Physical and biochemical characterizations of the soil material (air-dry < 2 mm), including pH_{water} (1 : 2 w/v), carbon (C) and nitrogen (N) concentrations, and particle size distribution.

Catchment and hillslope positions	Depth (cm)	pH_w^a	C ($g\,kg^{-1}$)[b]	N ($g\,kg^{-1}$)[c]	C : N ratio	Clay ($g\,kg^{-1}$)	Silt ($g\,kg^{-1}$)	Sand ($g\,kg^{-1}$)	SSA ($m^2\,g^{-1}$)
P303 transect P4									
Crest	0–10	6.2	54.0	2.6	20.9	117	365	518	6.96
	10–20	5.4	35.6	1.6	21.6	106	371	523	9.27
Backslope	0–10	6.3	85.4	3.4	25.1	122	375	503	11.99
	10–20	6.5	32.2	1.4	22.8	106	371	524	17.09
Depositional	0–10	6.5	9.7	0.5	19.2	163	378	459	7.12
	10–20	6.1	33.3	1.2	26.8	162	374	464	9.17
B204 transect B8									
Crest	0–10	5.4	46.4	1.7	27.2	183	357	460	11.52
	10–20	5.3	18.4	0.7	27.1	184	368	449	14.15
Backslope	0–10	5.1	31.9	4.1	7.8	145	381	474	8.61
	10–20	5.1	27.5	0.8	35.7	159	368	473	9.74
Depositional	0–10	nd[e]	167.8	5.2	32.4	113	378	509	3.68
	10–20	nd	133.7	3.4	39.2	114	395	491	3.46

[a] Standard error ≤ 0.06 for analytical replicates.
[b] Standard error ≤ 0.02 for analytical replicates.
[c] Standard error ≤ 0.7 for analytical replicates.
[d] $n = 3$ analytical replicates.
[e] Some samples were not measured due to lack of material (indicated by nd for no data).

BGD
12, 2491–2532, 2015

Table 3. Coefficients of variation (SD relative to the mean, expressed in %) for sediment yield, carbon (C) and nitrogen (N) concentrations, and carbon to nitrogen (C : N) mass ratios averaged across years for each catchment, and averaged across catchments for each water year within the Kings River Experimental Watershed. Archive samples from 2006 were not available for sampling (indicated by no data – nd).

Averaged across all years for each catchment				
Catchment	Sediment yield	%C	%N	C : N
D102	109.4	36.0	44.5	13.5
P301	111.5	61.7	67.7	16.3
P303	195.1	74.9	71.4	11.8
P304	93.0	62.6	67.4	14.6
B201	107.7	42.1	46.5	10.9
B203	121.3	67.1	72.7	9.0
B204	107.9	80.1	99.6	22.8
T003	140.8	37.1	45.2	14.5
Averaged across all catchments for each water year				
Year	Sediment yield	%C	%N	C : N
2005	69.5	40.9	46.8	22.3
2006	92.8	nd	nd	nd
2007	115.8	36.6	36.8	13.1
2008	165.5	46.4	44.2	14.0
2009	78.1	46.0	44.3	12.7
2010	68.0	66.0	64.7	13.8
2011	135.9	89.4	84.9	18.6

BGD
12, 2491–2532, 2015

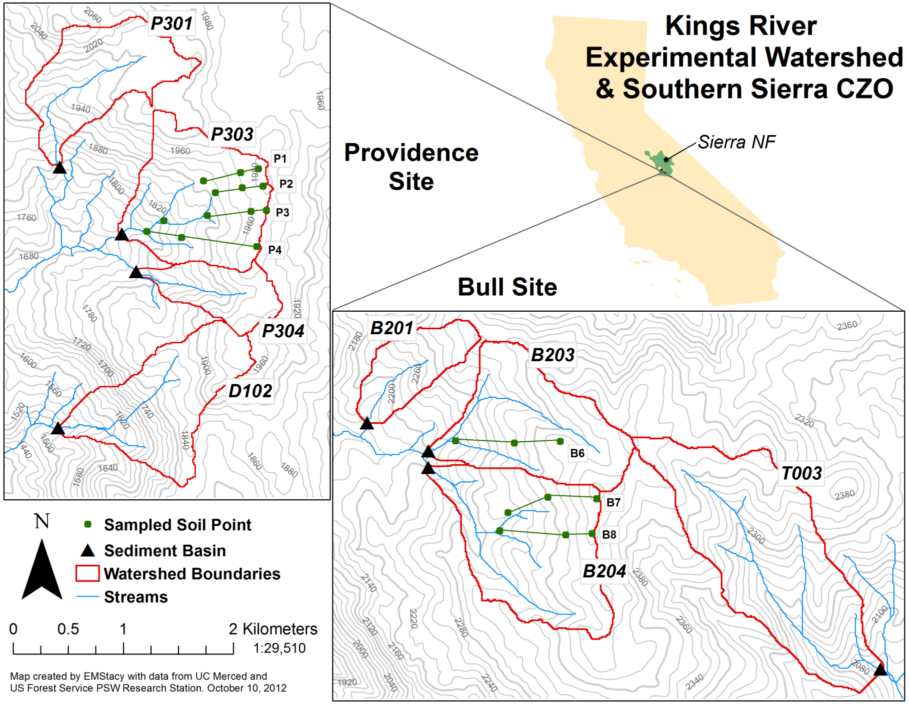


Figure 1. Map of the Kings River Experimental Watershed and Southern Sierra Critical Zone Observatory showing soil sampling points (green circles, at depositional, backslope, and crest hillslope positions from left to right along transects) and sediment sampling basins (black triangles).

BGD
12, 2491–2532, 2015

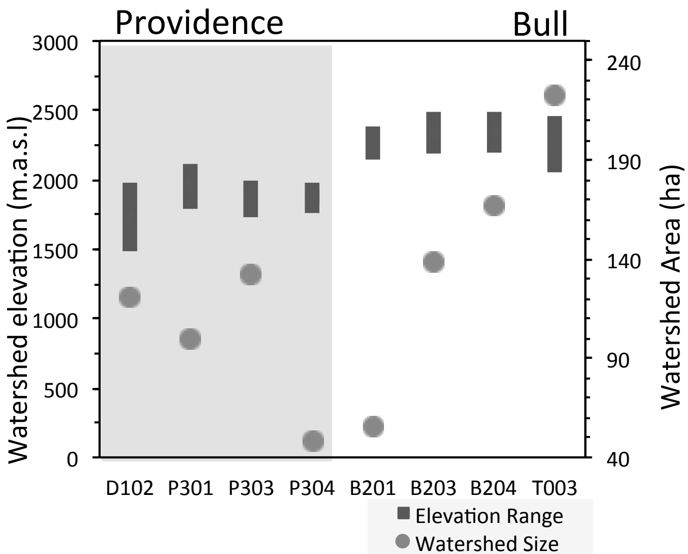


Figure 2. Elevation and size of the catchments. Roughly half of the precipitation at the lower-elevation Providence catchments falls as rain, while the Bull catchments (high elevation) receive > 75 % of precipitation as snow.

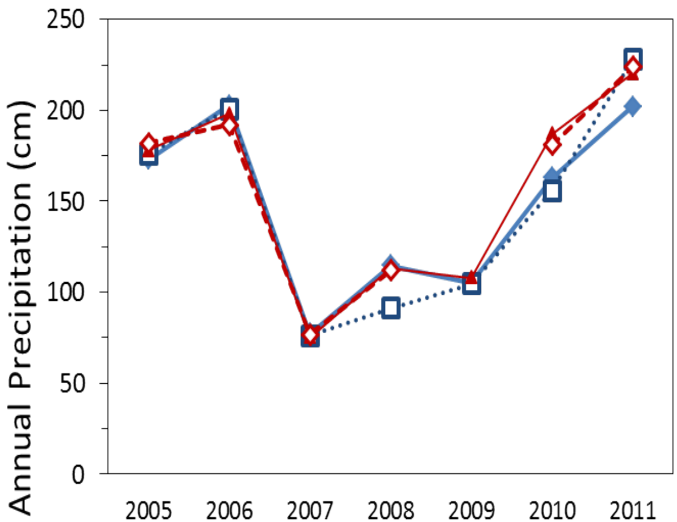
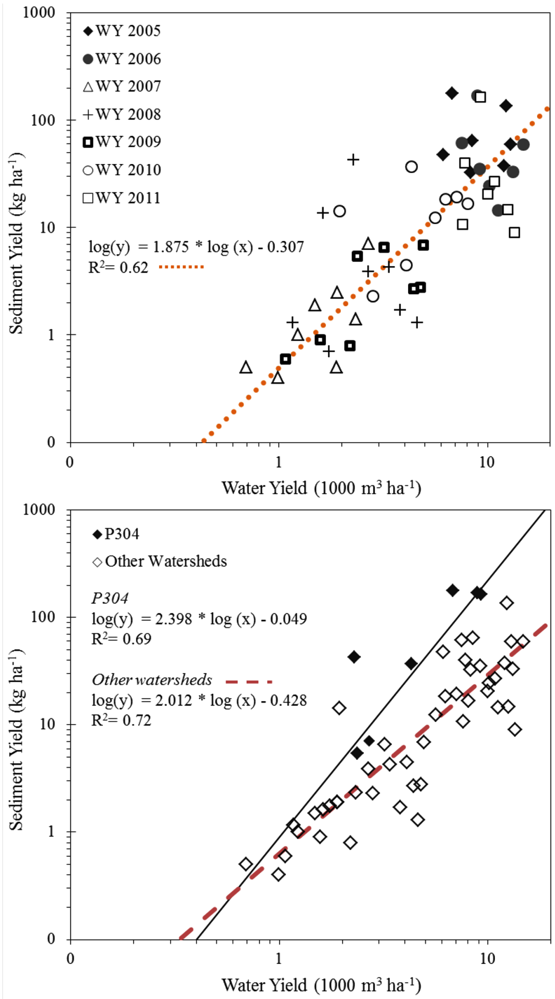


Figure 3. Annual precipitation from four meteorological stations – two at the Providence site (lower elevation; blue symbols) and two at the Bull site (upper elevation; red symbols) during the years of the study. The meteorological stations are sited at low and high elevations within each group of catchments.

BGD
12, 2491–2532, 2015



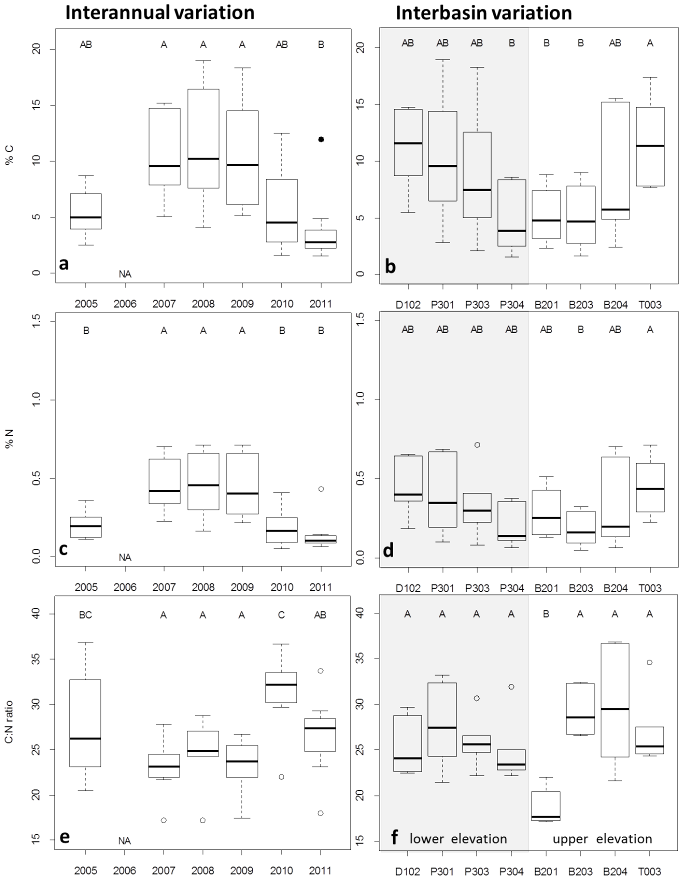
BGD
12, 2491–2532, 2015

Soil carbon and nitrogen erosion in forested catchments in the Sierra Nevada

E. Stacy et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Figure 4. Relationships between annual sediment yield (including mineral, coarse and fine organics) and annual water yield for the Kings River Experimental Watershed catchments. Excluding the four outliers increased the correlation coefficient to 0.64, but excluding the P304 catchment (outlier value in 5 of 7 years when each year is examined independently) increases the correlation to 0.72. Sediment data from catchment B203 in 2009 were excluded from both analyses because missing data for water yield.



BGD
12, 2491–2532, 2015

Soil carbon and nitrogen erosion in forested catchments in the Sierra Nevada

E. Stacy et al.

Figure 5. Carbon (C) and nitrogen (N) concentrations and carbon to nitrogen (C : N) mass ratios of < 2 mm material collected in sediment basins within the Providence (low-elevation) and Bull (high-elevation) catchments between water years 2005 to 2011. Left panels (**a**, **c**, and **e**) show interannual variation in these variables, while right panels (**b**, **d**, and **f**) show interbasin variation (Providence catchments highlighted by shading). The bold line in the boxplot marks the median, and boxes mark the interquartile range, with the full range indicated by the fences save for outliers more than 1.5 times the box width from the box edge, marked by a circle. Different means as determined by ANOVA using Tukey HSD test ($\alpha = 0.05$) are designated by letters. Archive samples for 2006 were not available for testing, indicated on the graph by NA for not available.

BGD
12, 2491–2532, 2015

Soil carbon and nitrogen erosion in forested catchments in the Sierra Nevada

E. Stacy et al.

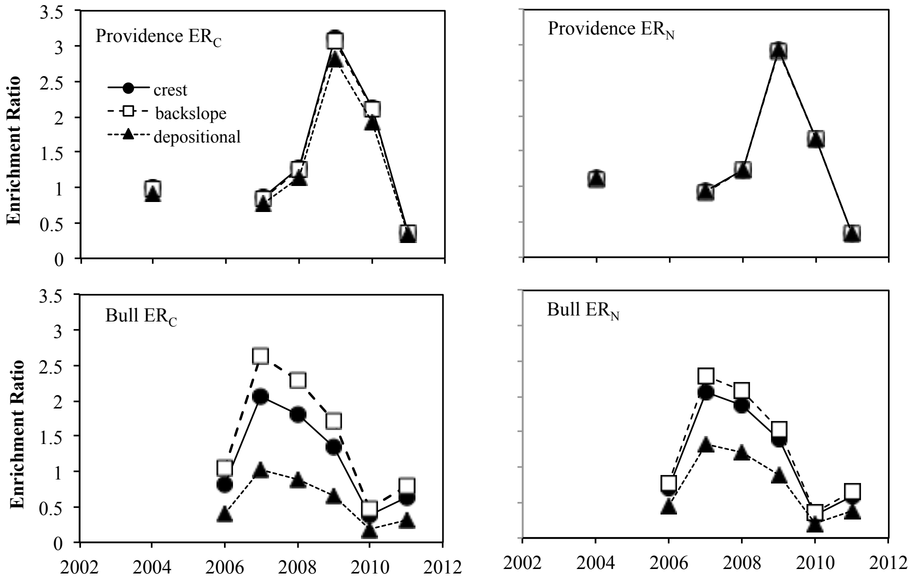


Figure 6. Enrichment ratios for carbon (ER_C) and nitrogen (ER_N) in material (< 2 mm) collected from sediment basins at the outlet of each catchment over the water years 2004–2011. Different symbols represent enrichment ratios calculated using topsoil (0–10 and 10–20 cm) from one of the three distinct hillslope positions we studied (crest, backslope, and depositional) in the Providence (low elevation) and Bull (high-elevation) catchments. Sediment basins were installed 2002–2004 and archives were not preserved for many sediment basins prior to 2006.

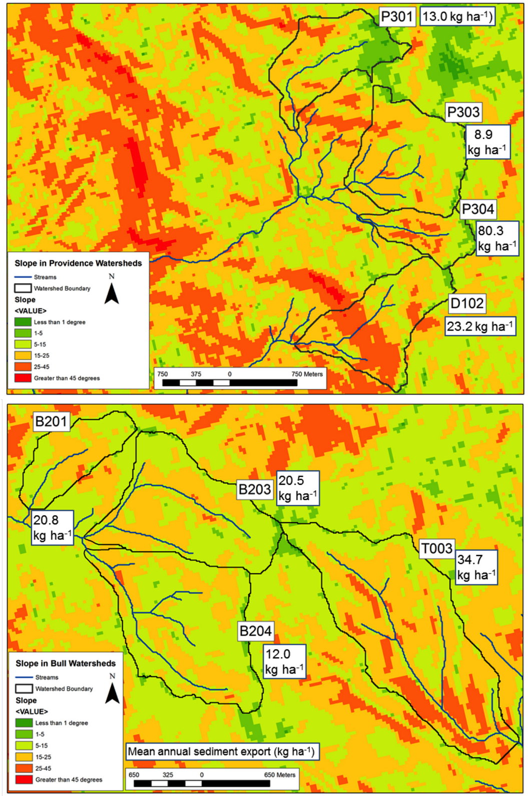


Figure 7. Slopes in the eight catchments are moderately steep as shown by a weighted scale ($< 1^\circ$ dark green; 1–5° medium green; 5–15° chartreuse; 15–25° light orange; 25–45° dark orange; $> 45^\circ$ red). Flat areas in crest and depositional locations are very small. Slope values calculated from a 10 m digital elevation model. Mean annual sediment export is given for water years 2005–2011.

BGD

12, 2491–2532, 2015

Soil carbon and nitrogen erosion in forested catchments in the Sierra Nevada

E. Stacy et al.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion