Measurements of coarse particulate organic matter transport in steep mountain streams and estimates of decadal CPOM exports

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Abstract

Coarse particulate organic matter (CPOM) provides a food source for benthic organisms, and the fluvial transport of CPOM is one of the forms in which carbon is exported from a forested basin. However, little is known about transport dynamics of CPOM, its relation to discharge, and its annual exports from mountain streams. Much of this knowledge gap is due to sampling difficulties. In this study, CPOM was sampled over one-month snowmelt high flow seasons in two high-elevation, subalpine, streams in the Rocky Mountains. Bedload traps developed for sampling gravel bedload were found to be suitable samplers for CPOM transport. CPOM transport rates were well related to flow in consecutive samples but showed pronounced hysteresis over the diurnal fluctuations of flow, between consecutive days, and over the rising and falling limbs of the high-flow season. In order to compute annual CPOM load, hysteresis effects require intensive sampling and establishing separate rating curves for all rising and falling limbs. Hysteresis patterns of CPOM transport relations identified in the well-sampled study streams may aid with estimates of CPOM transport and export in less well-sampled Rocky Mountain streams. Transport relations for CPOM were similar among three high elevation mountain stream with mainly coniferous watersheds. Differences in among streams can be qualitatively attributed to differences in CPOM contributions from litter fall, from the presence of large woody debris, its grinding into CPOM sized particles by gravel-cobble bedload transport, hillslope connectivity, drainage density, and biological consumption. CPOM loads were 3.6 and 3.2 t/yr for the two Rocky Mountain streams. Adjusted to reflect decadal averages, values increased to 11.3 and 10.2 t/yr. CPOM yields related to the entire watershed were 2.7 and 4 kg/ha/year for the years studied, but both streams exported similar amounts of 6.5 and 6.6 kg/ha/year when taking the forested portion of the watershed into account. To reflect decadal averages, CPOM yields per basin area were adjusted to 8.6 and 12.6 kg/ha/year and to 21 kg/ha/year for the forested watershed parts. CPOM yield may be more meaningfully characterized if

annual CPOM loads are normalized by the area of a seam along the stream banks together with the stream surface area than by the entire or the forested watershed area.

Key words

Rocky Mountains

Mountain streams

Sampling methods and schemes

Transport relations

Hysteresis

Carbon export

1. Introduction

1.1 Background

Coarse particulate organic matter (CPOM) comprises leaves, needles, coniferous cones, twigs, sticks, branches, bark pieces, wood fragments, and small logs. CPOM particle sizes range from 1 to about 100 mm (Naiman and Sedell, 1979), but the upper size limit is poorly defined (Turowski et al., 2013). CPOM particles play an important role as a food source for benthic organisms (e.g., Fisher and Likens, 1973). Furthermore, fluvial transport of CPOM is one of the forms in which carbon is exported from a catchment (Turowski et al., 2016; West et al., 2011; Wohl and Ogden, 2013). CPOM may contribute as little as 2.5 - 10% to total carbon export (Wallace et al., 1995, 1997; Richardson et al., 2005), but also substantially higher fractions of up to 80%, particularly in quickly eroding catchments (Seo et al., 2008; Turowski et al., 2016). Knowledge of CPOM transport rates is needed when establishing watershed carbon budgets that account for input, consumption, retention, and export. Fresh CPOM is supplied to a stream, e.g., as litter fall, and branches, and tends to be transported on the surface over relatively short distances (up to several 100 m, Jones and Smock, 1991; Webster et al., 1994, 1999; Wallace et al., 1995) before becoming trapped around obstacles (Osei et al., 2015) where particles become waterlogged, sink, and accumulate on the stream bottom (cf., Ruiz-Villanueva et al., 2016; Turowski et al., 2016). Submerged CPOM (including litter and woody debris) experiences carbon leaching, microbial colonization (conditioning), shredding by invertebrates, and physical abrasion (Harmon et al., 1986; Merten et al., 2013; Foucreau et al., 2013). In snowmelt regimes, when CPOM deposits are re-entrained at the beginning of the high-flow season, fully waterlogged CPOM from the channel bed, together with CPOM supplied from hillslopes and some dry CPOM that had been stranded along the banks, is transported through the channel network and exported. Ample information has been compiled on annual carbon exports in the form of fine organic material <1 mm (FPOM) contained in suspended sediment samples (e.g., Worrall et al., 2014, Madej, M.A., 2015) and in the form of large woody debris

(e.g., Piégay et al., 1999; Seo et al., 2008). However, little is known about carbon export of CPOM, the intermediate size (Webster and Meyer 1997; Turowski et al., 2016), and information is especially scarce for high elevation Rocky Mountain streams where large tracts of forested land are located in the US. This study makes a start towards filling this gap.

Because CPOM is lightweight (compared to inorganic bedload) and easily entrainable by flow, instantaneous transport rates of waterlogged CPOM are influenced by the interplay between (local) flow hydraulics and the dynamics of storage and release from local retention within the streambed and along the banks; hence transport rates are variable over time and with water discharge. Several publications have suggested or shown that CPOM transport rates respond quickly to increased flow rates (Edwards, 1980; Beschta, 1981; 1983; Estep, 1983; Perry and Rose, 1984; Estep and Beschta, 1985; Wallace et al., 1995; Kiffney et al., 2000; Johnson et al., 2006; Beschta and Jackson, 2008; Turowski et al., 2013, 2016; Bunte et al., 2015c). Information on CPOM transport dynamics is needed when establishing an organic matter budget (Webster and Meyer, 1997; Richardson, 1992; Richardson et al., 2005, 2009) and insights into transport dynamics would aid in estimating CPOM export in poorly sampled streams. However, temporal dynamics of CPOM transport over an annual high flow season have not yet been described.

1.2 Previous sampling approaches

Difficulties in measuring the downstream conveyance of CPOM have posed the biggest challenge to advancing insights into its transport dynamics. CPOM export from a basin can be quantified by excavating and analyzing the annually accumulated material in debris basins (Bilby, 1981), but that practice reveals no insights into seasonal transport dynamics. The collection of all mobile CPOM in a screened sampling box under an overfall and emptying the box episodically, biweekly or daily during high flows (Wallace et al., 1995; Johnson et al., 2006), is a workable practice reserved to small streams

draining catchments of a few ha (1 ha = 100 x 100 m) in size and with discharges of a few liters/second. In larger streams, only portions of the CPOM transport can be sampled. Placing drift nets into the water column for minutes or hours at a time, episodically throughout the year (e.g., Newbern et al., 1981; Perry and Rose, 1984; Angradi, 1991; Jones and Smock, 1991; Kiffney et al., 2000) is limited to tranquil flows. Edwards (1980), Beschta (1981, 1983) and Estep (1983) collected fine POM (< 1 mm) and the fine portion of CPOM during stormflow events as by-catch in bedload samples in a 7.6 by 7.6 cm opening Helley-Smith sampler with a 0.2 mm mesh-width net. However, those measurements are limited to the bottom 7.6 cm of the water column and miss organic matter carried higher up. Turowski et al. (2013, 2016) collected coarse CPOM samples over several years in a Swiss mountain torrent and presented the only well-sampled transport relation known so far. They sampled the entire water column using bedload traps 0.2 m high (Bunte et al. 2007, 2008, 2010) with a 6-mm mesh bag at moderate flows and switched to large basket samplers (1 m³) that temporarily move under an overfall at high flows (Rickenmann et al., 2012).

Considering the lack of insight into transport dynamics and export of CPOM—the size range between FPOM and large woody debris—this study was conducted to:

- 1) demonstrate use of bedload traps for sampling CPOM transport in high-energy but wadeable mountain streams during a high-flow season,
- 2) document CPOM transport relations with discharge and their daily and seasonal hysteresis over a snowmelt high-flow season,
- 3) provide estimates of annual CPOM export in two high elevation Rocky Mountain streams and compare them to CPOM export in a Swiss mountain stream, and
- 4) suggest that hysteresis patterns and transport relations identified in the two study streams aid in prediction of CPOM transport in other mountain streams with coniferous watersheds.

2. Study sites

CPOM samples were collected in conjunction with gravel bedload sampling in two cobble-bed streams in subalpine catchments in the Rocky Mountains. The studies were conducted in 2001 and 2002 (Bunte, 2001; Bunte and Swingle, 2003), about 10 years before the widespread onset of pine beetle kill in the central Rocky Mountains. Both study streams have snowmelt runoff regimes and daily fluctuations of flow. Study site and basin characteristics are summarized in Table 1.

2.1 Little Granite Creek

The Little Granite Creek study site (**Error! Reference source not found.a**) in NW Wyoming is located 3.3 km above the confluence with Granite Creek. Downstream of Pleistocene glaciated headwater areas, the valley is typically confined by forested hillslopes (Lodgepole Pine (*Pinus contorta*), Engelmann Spruce (*Picea engelmannii*), Douglas Fir (*Pseudotsuga menziesii*)), but opens to a 45 to 50 m wide meadow 135 m upstream from the sampling site. The stream is incised about 1.1 m into the valley fill, keeping most high flows confined to the channel. The sampling site was located within a 25-m long straight run. Flow stage elevation was digitally recorded in 15-minute increments. Flow velocity was measured almost daily at about 20 verticals across the channel with an electromagnetic current meter at 0.6 of the flow depth to compute discharge and establish a hydrograph. Bankfull flow (Q_{bf}) was estimated from field evidence and from the long-term flow record of a near-by stream adjusted by drainage area of the study stream.

2.2 East St. Louis Creek

East St. Louis Creek is a steep, cobble-bed mountain stream (**Error! Reference source not found.b**) in the Fraser Experimental Forest (<http://www.fs.usda.gov/main/fraser/about/site-description>) in central

Colorado. The drainage basin is covered by glacial till, and most of the basin is located in subalpine forest (Engleman spruce, Subalpine fir (*Abies lasiocarpa*), Lodgepole pine); there are a few quaking aspen (*Populus tremuloides*), alder (*Alnus incana*), and willows (*Salix* species). The streambed is typically incised by about 1 m, which prevents extensive overbank flooding. The sampling site was located in a short and locally wide plane-bed section a few meters upstream of a weir pond where discharge is recorded continuously at a crested weir. Bankfull flow (Q_{bf}) was taken as the 1.5-year recurrence interval flow ($Q_{1.5}$) of a long-term flow record.

3. METHODS AND ANALYSES

3.1 Sampling with bedload traps

Bedload traps (Bunte et al., 2004, 2007, 2008, 2010) were used for sampling CPOM transport together with gravel bedload in this study (Bunte, 2001; Bunte and Swingle, 2003). The trap openings are 0.2 m high, 0.3 m wide, and 0.1 m deep, are made of aluminum, and have the shape of a shoebox without a bottom placed on its long side. A net 1 to 1.6 m long with a 3.6 mm mesh width is attached to the frame (Fig. 2a). The frame is placed onto a 0.41 by 0.35 m aluminum ground plate that is installed flush with the average height of the bed and anchored to the stream bottom with two metal stakes that are pounded into the bed. Adjustable straps attached to the frame are tied around the metal stakes, and they hold the samplers in place. Because bedload traps are not handheld, they can be deployed for sampling times ranging from minutes to hours depending on transport rates and fill level of the net. For emptying, the string that closes the net at its downstream end is untied, the contents are shaken into a large bucket, and the string is re-tied for another round of sampling. Samples can thus be taken back-to-back during a field day, while the sampler frames remain fastened on the ground plates (Fig. 2b). Four traps were installed about 1 m apart across the stream at the two study sites. Samples were collected with the bedload traps over 8 to 10 hour periods between the daily falling limbs of flow in the morning

and the daily rising limbs up to or just past daily peak flow in the evening. Bedload traps were removed from the stream bed overnight to avoid overfilling them.

3.2 Sampling scheme

At Little Granite Cr., the 2002 snowmelt runoff had two distinct peaks, one on May 21 (85% Q_{bf}) and one on June 1 (110% Q_{bf}) (Fig. 3a). CPOM sampling started at 21% Q_{bf} on the first rising limb with 1-hour samples and continued daily until the end of the first discharge peak two weeks later. Over the second discharge peak, samples were collected alternately over intervals of 10 and 60 minutes. Sampling extended over another two-week period until flow had decreased to 40% Q_{bf} on the second falling limb. Five to eight samples were collected each day, totaling 92 samples over the four-week high-flow season. At East St. Louis Cr., all CPOM samples were collected over 1-hour periods, starting at 44% of Q_{bf} a week into the snowmelt high flow season, covering peak flow that was 70% of Q_{bf} , and ending 17 days later at 36% of Q_{bf} (Fig. 3b). Two to seven samples were collected per day on most days, totaling 73 samples.

3.3 CPOM composition and transport modes

Most of the CPOM collected in the bedload traps consisted of small cones from coniferous trees, cone scales, coniferous needles, small twigs and sticks (typically 10 to 30 mm in diameter and 50 to 300 mm long), leaves (mainly willow and alder), small, spongy pieces of wood, and occasional hard pieces of bark. CPOM sampled in this study did not include branches and small logs. Most of the sampled CPOM was a dark brown, particulate, stringy mass and appeared as thoroughly soaked duff from the forest floor (Fig. 4). Dry needles were more frequent early in the high-flow season; at higher flows, sticks joined the CPOM mixture; only a few larger branches passed the sites but they were not sampled in the bedload traps. Later in the high-flow season, rain, sleet, and hail washed, dislodged, and tore off dry needles and the green tips of coniferous trees that were included in the sampled CPOM mix together

with parts of fresh herbaceous plants. The CPOM composition in the study streams is similar to the CPOM contained in bedload samples the authors collected in other Rocky Mountain streams.

The density of waterlogged CPOM particles is slightly higher than that of water; hence, those particles are not buoyant as opposed to large wood pieces (Ruiz-Villanueva et al., 2016). When water flow was still clear during moderate high flows, the authors observed CPOM to travel as bedload, rolling, sliding, and bouncing along the bed surface, especially the plump conifer cones and soaked wood pieces. At larger flows, CPOM moved in larger hops and in near-bed suspension; small organic particles moved as suspended load within the water column, while sticks floated. As flow approached the bankfull level, the water was turbid, and the channel bed was not visible.

3.4 Sample processing and computation of CPOM transport rates

Early in the highflow season, material collected in bedload traps comprised mostly CPOM but little gravel (Fig. 4). Sample volumes reached 20 liters per trap during the first notable daily peak in the high flow season. The CPOM portion decreased to less than half this volume later in the high-flow season. CPOM was typically separated from gravel bedload in the field (see description by Bunte et al., 2015), and the volume of wet CPOM samples was determined in a clear 500 ml measuring cup or in a graded 10-liter bucket.

Wet volumetric CPOM transport rates ($Q_{CPOM\ vol}$; l/hour) were individually computed for each of the four segments of stream width represented by one of the four bedload traps because lateral spacing and sampling time differed slightly between traps. Summing over all width segments (that make up the total stream width) yields the cross-sectional wet volumetric CPOM transport rate. A dozen CPOM samples from each of the two streams were dried to constant weight in a low temperature oven. The dry mass

transport rate Q_{CPOM} (g/hr) was obtained from multiplying the wet volumetric transport rate by the mean dry bulk density of 112 g/l at E. St. Louis Creek (standard deviation of 11.2 g) and 93.3 g/l at Little Granite Creek (standard deviation not recorded).

3.5 Adjustment for unsampled CPOM passing over the traps

Flow sometimes overtopped the bedload traps—that extend 0.2 m into the water column—leaving CPOM traveling near the surface unsampled. At Little Granite Creek, flow started to overtop the two central traps at 20% Q_{bf} and the two lateral traps at 30% Q_{bf} . The maximum overflow height reached 0.22 m above a trap during the brief periods of peak flow. To estimate the unsampled CPOM portion, a vertical concentration profile of CPOM needs to be assumed. Three scenarios were considered: If the concentration of waterlogged CPOM particles (C_{CPOM} [g/m³]) is highest near the stream bottom (as is common for coarse suspended sediment and low turbulence), and given a near logarithmic velocity profile with the fastest flow (v [m/s]) near the water surface, then CPOM transport rates per depth and width increment (Q_{CPOM} [g/m²·s] = $C_{CPOM} \cdot v$) are approximately even throughout the water column (Fig. 5a). If, by contrast, the vertically distribution of C_{CPOM} is roughly even through the water column (as is common for high turbulence and fine suspended sediment), Q_{CPOM} is highest near the water surface (Fig. 5b). If large amounts of CPOM float near the water surface (as flows pick up dry sticks and branches from the banks and storms knock off a spray of needles and twigs), while waterlogged CPOM transport is concentrated near the bottom, Q_{CPOM} increases towards the water surface (Fig. 5c). In the latter two cases, notable portions of CPOM transport may be missed by not sampling the top portion of the water column.

Based on visual field observation when flows were sufficiently clear, a downward increasing trend was recognized for C_{CPOM} within the water column (also reported by Beschta, 1983), the result of which is a

vertically approximately even distribution of Q_{CPOM} (Fig. 5a). The observation should hold to at least moderately large flows, and it was extended to bankfull flows in the two study streams out of necessity. With a downward increasing trend in C_{CPOM} , the unsampled portion of CPOM transport is proportional to the height of flow overtopping the traps h_{top} (Fig. 6). Overtopping heights were recorded at various flows Q for all traps, and h_{top} was described by logarithmic functions of Q where x and m are regression coefficients.

$$h_{top} = x (\log Q) + m \quad (2)$$

Once Q started overtopping one of the traps, overtop-adjusted transport rates $Q_{CPOM\ adj}$ were computed from measured transport rate $Q_{CPOM\ meas}$ as

$$Q_{CPOM\ adj} = h_{trap} + \frac{h_{top}}{h_{trap}} \cdot Q_{CPOM\ meas} \quad (3)$$

where the trap height h_{trap} is 218 mm and included the frame and the net thickness. During the brief peak flow periods, the overtop-adjusted cross-sectional $Q_{CPOM\ adj}$ rates at Little Granite Creek were up to twice the sampled values, and overtopping adjustments increased the unadjusted CPOM load by about 160% over the course of the hydrograph. At East St. Louis Creek, flows did not exceed 70% Q_{bkf} , and the sampling site was also considerably wider than the average stream width. Hence, flow overtopped only one of the four traps by maximally 6 cm at the highest measured flow. The overtopping adjustment increased cross-sectional CPOM transport rates by less than 6% for those flows.

3.6 Adjustment of 1-hour samples at Little Granite Creek

In order to assess the effect of sampling time on measured gravel transport rates (Bunte and Abt, 2005), sampling times at Little Granite Creek were alternated between 1 hour and 10 minutes. A power function regression of CPOM transport rates computed from 10-minute samples ($Q_{CPOM\ 10}$) vs. those computed from 1-hour samples ($Q_{CPOM\ 60}$) at the same discharge shows a well-defined relation (Fig. 7). Differences in capture rates between the two sampling times were negligible at low transport rates, but $Q_{CPOM\ 10}$ was about twice as large as $Q_{CPOM\ 60}$ at the highest transport rates near peak flow, suggesting that 1-hour samples had a reduced sampling efficiency because the nets had overfilled with CPOM or had clogged. To compensate for the reduced sampling efficiency, the fitted regression was applied to adjust the 1-hour samples to transport rates that might have been obtained by 10-minute sampling. CPOM transport rates < 10 g/min did not require adjustment because sampling time had minimal effect on sampling efficiency. After adjustments, 91 individual CPOM transport rates were available over the high-flow season for computation of annual CPOM export at Little Granite Creek. At East St. Louis Creek, peak flow (70% Q_{bf}) and maximum Q_{CPOM} (81 g/min) were much lower, so a reduction in sampling efficiency of 1-hour samples was unlikely, and all 73 collected 1-hour samples were used without time adjustment to compute CPOM transport relations.

3.7 Relation of CPOM transport rates to discharge

Measured CPOM transport rates (adjusted for overtopping and long sampling times where needed) extended over more than two orders of magnitude in both study streams (Fig. 8a and b). For a given discharge, Q_{CPOM} scattered over an order of magnitude in both streams due to pronounced hysteresis (see discussion section). At East St. Louis Cr., the exponent b fitted to the relation $Q_{CPOM} = a \cdot Q^b$ for all data is 4.5, while exponents for individual rising and falling rating curves range between 6.6 and 7.1. At Little Granite Cr., Q_{CPOM} increases less strongly with flow, yielding an exponent of 3.5 for all samples,

while exponents for individual limbs of flow are within 3.0 and 4.1. The fit of all CPOM data per site to a power function transport relationship $Q_{CPOM} = a \cdot Q^b$ is moderate (r^2 of 0.60 and 0.73), but much improved (r^2 of 0.85 to 0.96) when power functions are fitted to the individual rising and falling limbs (Fig. 8a and b). The pronounced differences of transport relations between rising and falling limbs and from the relation for all data clearly shows that separate CPOM rating curves are required to compute CPOM load over the high-flow season.

3.8 Computation of seasonal CPOM loads

A summation approach that is based on a dense time series of measured transport rates is generally considered the most accurate way to compute seasonal or annual load (Walling and Webb, 1981, 1982, 1987, 1988). Extensive sampling at both study streams allowed developing a times series and bridging of a few unsampled days. The sequence of 4 to 10 CPOM transport rates over the daily rising limbs of flow (adjusted for sampler overtopping and overfilling where needed) generally followed the diurnal fluctuations of flow. The lowest and highest daily transport rates fell close to the daily minima and maxima of flow at both streams. This allowed extending the observed daily trends of Q_{CPOM} to unsampled peak- and low-flow times to estimate daily maximum and minimum Q_{CPOM} for unsampled days. For times between the daily minima and maxima of flow, the CPOM flux was interpolated geometrically to obtain a value for each 15-minute time increment. This step created a 15-minute time series of estimated of CPOM transport rates over the high-flow season (Fig. 3a and b). Multiplication of Q_{CPOM} by 15-minute time increments and summing produced the CPOM load for the sampled portion of the high flow season.

A rating curve approach was used to compute CPOM loads for the unsampled pre- and post high-flow seasons, extending sampled trends for the first rising limb and the second falling limb, respectively, to

flows before and after the immediate high flow period. At Little Granite Cr., hydrographs were not available for the 80-day remainder of the seasonal falling limb between July 12 and Sept. 30, and a constant value of $Q_{CPOM} = 0.05$ g/min was assumed. Zero CPOM transport was assumed for both streams between fall and spring when flows are very low (5-10% of bankfull), and a snow cover shields most of the stream surface from CPOM input.

3.9 Simulating a hydrograph with bankfull flow for East St. Louis Creek

Depending largely on the high flow magnitude and on the supply of CPOM to the stream, annual CPOM exports may vary 10-fold for a stream over time (Bilby, 1981; Wallace et al., 1995). When only one year is analyzed to estimate annual load, that high flow season should represent a “normal” year that may be defined as one in which flows exceed the bankfull level for a few days. While the 2002 season at Little Granite Creek peaked at bankfull and almost fulfilled this request, East St. Louis Creek in 2001 peaked at only 70% of bankfull flow. To mimic a similar hydrograph for East St. Louis Creek, peak flow was mathematically elevated to 100% of bankfull in this study, and all flows during the high flow season were increased proportionately. CPOM transport rates were then estimated by extrapolating the rating curves established for rising and falling limbs of flow in 2001 (Fig. 7b), applied to each 15-minute time increment, and summed over the elevated snowmelt hydrograph. CPOM supply at East St. Louis Creek was considered sufficient to permit extrapolation of the measured CPOM rating curves to bankfull flow because measured CPOM transport rates during a small flow peak on the falling limb of the hydrograph at the end of the high-flow season were higher than those predicted from the falling limb rating curves that were based on measurements early on the falling limb (see also the discussion on hysteresis).

4. Results

4.1 Annual CPOM export in the two study streams

Annual CPOM load computed for 2002 at Little Granite Creek was 3.6 metric tonnes (t). The vast majority (97%) of the annual export occurred during the 1-month high-flow season (Table 2), while only 0.4, 2.8, and 0.2% of the annual CPOM export occurred prior to high flow, after high flow, and later during summer low flows, respectively.

Annual CPOM load at East St. Louis Creek was 169 kg during the sampled 2001 low-flow year. Most of the CPOM export occurred within the high-flow period (84%), although notable amounts (15%) were supplied during the falling limb (see 2001 in Table 3). Annual CPOM export at East St. Louis Cr. for a simulated bankfull hydrograph (see bf-year in Table 3) reached 3.2 metric tonnes, 19 times more than computed for the 2001 low-flow year, and 99% of the export was concentrated within the central 1-month period of the high flow season. While this estimate might have some uncertainty because trends measured in the low-flow rating curves were extrapolated to higher flows, it shows the important role that runoff plays in annual CPOM export from a basin. Other studies have shown that differences in CPOM export of more than an order of magnitude between years are not unusual (Bilby, 1981; Wallace et al., 1995). The annual CPOM load at East St. Louis Cr. (3.2 t) for the simulated bankfull hydrograph was slightly lower compared to that at Little Granite Creek (3.6 t).

4.1.1 Adjustment of annual CPOM loads and yields to reflect decadal averages

Compared to a decadal average value, estimates of CPOM loads in Tables 2 and 3 are conservative given that flows briefly touched bankfull. An adjustment is needed to reflect an average estimate over a longer time period, such as a decade of flows (but excluding extreme events). However, long-term measurements of CPOM are rare. Results by Wallace et al. (1995) and Bilby (1981) suggest that annual

CPOM yield might vary within a factor of about 10. Considering that the two computed CPOM loads for East St. Louis Creek represent lower flow years, a decadal mean value might be estimated as the geometric mean between the measurements (3.6 and 3.2 t/yr) and their 10-fold values (35.7 and 32.4 t/yr), yielding 11.3 and 10.2 t/yr, respectively. By analogy, CPOM yield per watershed area adjusts from 2.7 and 4.0 kg/ha/yr to 8.6 and 12.6 kg/ha/yr, while the CPOM yield from the forested parts of the watershed adjusts from 6.5 and 6.6 kg/ha/yr to 20.9 and 20.5 kg/ha/yr, respectively (Table 4).

4.1.2 Comparison of annual CPOM exports between streams

Mean annual CPOM yields of about 0.4 to 10 kg/ha/yr are reported for small deciduous watersheds (Table 4). Per forested watershed area, and adjusted to represent a decadal average, the CPOM yields of 20.9 and 20.5 kg/ha_{for}/year from the two subalpine Rocky Mountain watersheds are 2 to 50 times larger than yields from deciduous forests in the Atlantic NE (Bilby, 1981), the Atlantic SE (Wallace et al., 1995), and the Brazilian Mato Grosso (Johnson et al., 2006). Comparing CPOM yields from the forested portion of the watershed, the Erlenbach, draining a wet, temperate catchment with mainly coniferous forest in Switzerland had a CPOM yield 30 times larger than the two subalpine Rocky Mountain streams.

5. Discussion and Summary

5.1 Sampling challenges

5.1.1 Bedload traps suitable for CPOM sampling, but overtopping issue

Bedload traps are sufficiently sturdy to collect the large CPOM volumes at high flows, and they are deployable as long as flows remain wadeable. Deployment of several traps over the cross-section, the long sampling times, and back-to-back sampling over the entire day facilitated intensive sampling. Care should be taken not to overfill the nets, which may require a reduction in sampling times when loads are high.

Estimating the CPOM transport passing above the bedload traps is the largest issue with bedload traps. Extending the observation of a downward increasing trend of the CPOM concentration and the resulting vertically even distribution of CPOM transport rates to higher flows was a simplification necessary absent of information on how the CPOM concentration profile changes with flow. Had the concentration of CPOM become vertically evenly distributed at the highest flows, then more CPOM would have been transported in the upper portion of the water column than in the lower portion, and CPOM transport rates would have been underestimated. What supports the assumed vertically even distribution of Q_{CPOM} is that CPOM transport relations in this study are not only straight in log-log space (Fig. 7) as shown by Turowski et al. (2016) for the Erlenbach where using 1-m³ volume basket samplers (Rickenmann et al., 2012) at high flow avoided overtopping transport, but that the transport relations are also similarly steep (see discussion Section 5.4).

Bedload traps that extend through the water column at all flows would be desirable for a more complete capture of CPOM transport. However, taller traps most likely would bend backwards and become dislocated from the ground plates at the highest flows. Some of the overpassing CPOM transport may be captured in drift nets held briefly on top of the bedload traps.

Adjustments for CPOM overpassing the sampler are especially needed for CPOM samples collected in a 7.6 cm by 7.6 cm opening Helley-Smith sampler (H-S) that is constrained to the near-bottom portion of the water column. Additional adjustments of H-S samples are also needed to account for the finer particle sizes collected in the H-S (0.25 to 30 or 40 mm) and that sticks are typically not sampled. Consideration will also need to be given to the high hydraulic efficiency of Helley-Smith type samplers, their short sampling times and the propensity for clogging of fine mesh bags (Bunte et al., 2008, 2010).

Computation of annual CPOM load from the contents of debris basins is a possibility but can be problematic especially when a steep valley requires the pit to be deep, when the captured inorganic sediment volume largely exceeds the CPOM volume, when CPOM comprises mainly duff, cones and wood chips rather than small logs, and when sediment-CPOM deposit is heterogeneously distributed. Determining the CPOM load under those conditions requires a large sampling effort including complete emptying of the basin, detailed surveying of the excavated pile to quantify the volume, and intensive sampling of the pile to determine the CPOM portion (Bunte, 2002, Bunte and Swingle, 2003). By contrast, debris basins have been used for collecting drifting logs (e.g., Piégay, 2003; Seo et al., 2008).

5.1.2 Conifer needles entrapped in 4 mm mesh width

Bedload traps used in this study have a 3.6 mm mesh width, giving rise to the concern that the 1 - 3.6 mm portion of CPOM was not sampled representatively. The 3.6-mm mesh might pose a problem for sampling small, near-spherical particles, but less so for needles from coniferous trees, which were collected in large amounts. Once entrapped in the bedload trap net, needles roll over the net bottom or tumble in the flow rather than passing straight through the mesh. Sampler nets with 1-mm mesh were found unsuitable for collecting CPOM in bedload traps because CPOM easily clogs those nets (Bunte and Swingle, 2009), which reduces hydraulic and sampling efficiency (Bunte et al., 2015 b).

5.1.3 Branches and small logs not sampled in bedload traps

CPOM collected in the bedload traps excludes branches and small logs (up to 100 mm diameter), whereas the 1-m³ volume of the Swiss basket sampler accepts those pieces (Rickenmann et al., 2012; Turowski et al., 2013). This bias against branches and small logs did not play a large role in the two sampled years with relatively low snowmelt runoff, but will gain importance in years of large high flows.

Branches that get caught at night on the vertical stakes on which the bedload traps are fastened during the day need to be incorporated into the estimates of CPOM transport rates.

5.1.4 Sampling scheme

As important for the sampling success as the physical sampler characteristics is the sampling scheme with which the traps are deployed. In snowmelt runoff regimes, 97 and 99% of the annual CPOM export is concentrated in the central 1-month period of the high flow season (Table 2 and Table 3). Hysteresis of CPOM transport rates is pronounced and requires very intensive sampling, especially over the first days of the high flow season when transport rates span a wide range between daily low and daily peak flow. Collecting samples at the troughs and at the peaks of most of the daily fluctuations of flow enables one to establish a time series that serves as a basis for a summation approach.

5.1.5 Annual load from summation and rating curve approaches

Separate CPOM rating curves need to be established for each portion of the typically multi-peaked snowmelt hydrograph. For example, had CPOM at Little Granite Creek been sampled over only a few consecutive days during the 1st rising or 2nd falling limbs of flow), and had only those two rating curves (together with bias correction factor (Hirsch et al., 1993), e.g., the one proposed by Ferguson 1986, 1987) been used to compute annual loads, results would have been either 1.8 or 15.5 t/yr. By contrast, using the appropriate rating curve for each hydrograph limb resulted in a CPOM load of 4.5 t/yr. The rating curve fitted to all data produced a similar annual load of 4.6 t/yr, a match attributable to the intensive sampling effort.

Annual load from the rating curve approach (4.5 t/yr) was 25% larger than the 3.6 t/yr obtained from the summation approach (Table 2). This difference may be attributed to a temporary supply limitation.

Over the 1st rising limb, or at other times when discharge increases strongly compared to the previous day, CPOM transport rates may stop to increase shortly before peak flow or even drop during or shortly after peak flow (Fig. 8b), due to a temporary exhaustion of CPOM supply. The summation approach accounts for this patterns, whereas the rating curve approach “overshoots” and predicts transport rates that are too high for those flows. Alternatively, a branch passing the site might not have been included in the sample.

5.2 Hysteresis

The quick response of Q_{CPOM} to increasing flow in both streams indicates that CPOM is readily entrained and transported, i.e., transport is hydraulically controlled. However, the hysteresis relations, and transport rates that decrease over time, show that the response of CPOM flux to flow is also governed by the availability of CPOM supply that decreases over the course of the high-flow season.

The extremely supply driven (and limited) transport dynamics cause CPOM transport relations to differ drastically between individual rising and falling limbs of the high-flow hydrograph, as well as between the pre-and post-runoff seasons (Bilby and Likens, 1980; Wallace et al., 1995; Beschta and Jackson, 2008). At Little Granite Creek, the season’s first rising limb Q_{CPOM} was 4-5 times higher than Q_{CPOM} on the first falling limb, 3-4 times higher than on the second rising limb and about 6 times higher than on the second falling limb (Fig. 9a).

At East St. Louis Creek, Q_{CPOM} during the first rising limb was about 3 times higher than on the shared transport relation for the first falling and second rising limb (Fig. 9b) and about 6 times higher than on the second falling limb. During small rainfall peaks towards the end of the high flow season at East St.

Louis Creek, Q_{CPOM} approached the relationship of the first rising limb, suggesting that CPOM was still available for transport on the falling limb in this low-flow year (Fig. 9b).

5.2.1 Similar hysteresis patterns in both study streams

Hysteresis in CPOM transport rates (Q_{CPOM}) followed similar patterns in the two study streams and may be characterized by a series of parallel bands. During the 1st rising limb of flow, consecutive Q_{CPOM} samples describe sweeping non-closing loops within a broad band that spans a factor of 4-6. Those pronounced clockwise hysteresis loops indicate supply limitation on the daily falling limbs of flow. Within a specific day, all consecutively sampled Q_{CPOM} follow a common trend, but the trend differs vastly among consecutive days. Each new day with increasing flows seems to be tapping into new stores of CPOM supply, allowing the loops to increase each day as well. However, daily supply depletes quickly, and transport rates drop notably shortly after a day's peak flow.

During the 1st falling limb of flow, Q_{CPOM} drops and moves along the lower border of the center band which spans a factor of approximately two. CPOM stores accessible by a specified flow on the 1st rising limb have been depleted, especially for the less energetic falling limb flows. During the 2nd rising limb of flow, Q_{CPOM} remains within that center band but tends to move along its upper border in large clockwise hysteresis loops. On the 2nd falling limb, Q_{CPOM} drops to the lowest band that is also about a factor of two wide, and consecutive samples describe tight clockwise loops.

Q_{CPOM} typically remains well within its assigned bands and only a few samples stray from the trend.

Notable are the last samples of the high flow season collected at East St. Louis Creek. The generally low discharges of the high flow season that peaked at only 70% of bankfull flow did not deplete the annual CPOM stores. Also, the 2nd rising limb was lower than the 1st falling limb, and as a result of both, Q_{CPOM}

collected at the very end of the high flow season did not remain on the lowest band but instead jumped to the highest band. By analogy, the 2nd rising limb at Little Granite Creek exceeded the first peak which allowed flow to access untapped stores. As a result, Q_{CPOM} on the 2nd rising limb increased above the band of 1st falling/2nd rising flows and merged into the band associated with the first rising limb. Finding that CPOM transport rates range in a reasonably predictable manner within those three bands is useful to explain the hysteresis patterns and may help to fill gaps in CPOM records collected over the high flow season.

5.2.2 Watershed and flow events change hysteresis pattern

Hysteresis patterns described for the two sampled years of relatively low snowmelt high flows (Fig. 8) reflect a gradual supply and episodic export of CPOM. CPOM supplied from littler fall, decay and grinding of instream logs, as well as occasional bank erosion and surface runoff replenishes the CPOM stores over the low flow season. CPOM stores then episodically empty during the annual snowmelt high flow seasons. These annually similar dynamics of CPOM storage and release represent periods of relative stability for both the channel and the watershed. However, magnitude and timing of hysteresis patterns may change between years. Hysteresis becomes more pronounced following tree death from forest fires or beetle kill after which large amounts of CPOM and LWD are delivered to a stream. In this case, a watershed event drives CPOM supply and delivery (event-driven delivery (Wohl et al., 2012) in the classification compiled by Jochner et al. (2015)). Large hysteresis effects also occur if a large flow event mobilizes a log jam or beaver dam and releases the CPOM trapped and stored there over several years (Bilby, 1981; Beckman and Wohl, 2014; Jochner et al., 2015). The scenario represents an event-driven export (Jochner et al., 2015). By contrast, hysteresis patterns become subdued if log jams or beaver dam trap much of the CPOM.

5.3 Comparison of CPOM transport relations and export from steep mountain streams

5.3.1 Similarity in steepness of CPOM transport relations

Comparing the three CPOM transport relations measured with bedload traps (this study and the montane Swiss Erlenbach torrent (Turowski et al., 2013, 2016)) shows that power functions fitted to the Q_{CPOM} transport relations for the entire high flow season in the form of $Q_{CPOM} = a Q^b$ have similar exponents (Fig. 10). The exponents are $b = 3.46$ at Little Granite Creek, $b = 4.82$ at East St. Louis Creek, and $b = 4.14$ for the Erlenbach. The similarity suggests that CPOM transport relations from coniferous, high elevation mountain streams may generally have exponents within 3 to 5, a range much narrower than for gravel transport relations for which b -exponents between 4 and 18 have been reported in mountain streams (Bunte et al., 2008, 2014, 2015c). For gravel transport relations, much of this variability is due to differences in bedload supply and bed material conditions. For CPOM transport relations, supply differs among streams, but particle effects, such as hiding and exposure or the degree to which particles are stuck in the bed play much less of a role.

A sample size of three CPOM transport relations is low for a generalizing statement. What may alleviate the uncertainty is that power-function rating curves fitted to POM data collected in the Alaskan Trap Bay Creek (Estep, 1983) and two sites at the Oregon Flynn Creek, and at Oak Creek (Edwards, 1980; Beschta 1981, 1983) have exponents of 1.9, 2.3-2.6, 2.9, and 4.9. Those exponents are somewhat lower than the range of exponents in this study (3.5 to 4.8), but this is expected because the POM data represent finer particles than in this study (FPOM and fine CPOM), were collected in a small, 7.6 cm by 7.6 cm opening, Helley-Smith sampler, and were not adjusted for particle overpassing (cf. Sect. 5.1.1). Those data can therefore not be used for a comparison with CPOM transport rates sampled with bedload traps because the sampling methods in the POM studies produce considerably lower transport rates.

The range of CPOM transport rates for a given discharge (e.g., $0.5 \text{ m}^3/\text{s}$) becomes generally narrower among the two subalpine Rocky Mountain streams and at the montane Erlenbach torrent when flow is expressed in terms of unit discharge $q = Q/w$. For q below $0.1 \text{ m}^3/\text{m}\cdot\text{s}$, Q_{CPOM} is within a similar range for all three streams, and this reflects a hydraulically controlled transport of CPOM at low flow. The widening of the range of measured Q_{CPOM} for larger q is attributable to the CPOM transport relation at the Erlenbach being steeper for q than for Q , and this is because stream width increases with q in the trough-shaped channel. By contrast, stream widths remained almost constant over the sampled range of flows in the incised Rocky Mountain streams, causing transport relations to be equally steep in terms of Q and of q .

Compared to the wide range of variability of gravel bedload transport rates that span up to six orders of magnitude for a specified q (Bunte et al. 2008, 2014), CPOM transport rates for a specified q are rather similar among the three studied mountain streams in coniferous watersheds (Fig. 10b), considering that the Erlenbach (wet, temperate climate, high physical erosion rates, see also other factors discussed below) probably represents a high-end member of CPOM production, delivery to the channel, and fluvial export, while the two study streams (cold, dry climate, see also other factors discussed below) are likely lower-end members. The relatively narrow range between the high and lower members suggests that a rough estimate of a CPOM transport relation may be obtained for an unmeasured steep mountain stream in a coniferous watershed considering the factors that affect transport relations discussed below.

5.3.2 Reasons for differences in CPOM transport relations

Transport rates for East St. Louis Creek that are slightly higher than for Little Granite Creek may be explained by several factors:

- There is more moisture available in East St. Louis Creek given a northerly oriented catchment and frequent summer showers which increases primary productivity in a generally cold and dry environment of high-elevation Rocky Mountain streams.
- The same volume rate of wet CPOM ($V_{CPOM,wet}$) collected at each stream yields higher transport rates of dry CPOM (Q_{CPOM}) at East St. Louis Creek where the bulk density of oven-dried CPOM (ρ_{CPOM}) was larger (112 g/l) than at Little granite Creek (93 g/l), and $Q_{CPOM} = V_{CPOM,wet} \times \rho_{CPOM}$.
- The narrower channel of East St. Louis Creek with a closed canopy receives more CPOM from litter fall and banks per stream length than the wider Little Granite Creek.
- Waterlogged logs may be ground more efficiently into smaller CPOM pieces in East St. Louis Creek with a step-pool morphology and gravel transport rates that are about an order of magnitude larger per unit discharge than at Little Granite Creek with its plane-bed channel.
- There was more overtopping of unsampled CPOM at Little Granite Creek; Transport rates from Little Granite Creek might be underestimated if the adjustment was insufficient.

There are a number of reasons why the CPOM transport relation is lower in the two Rocky Mountain streams than at the Swiss Erlenbach. The two Rocky Mountain streams are located in subalpine forests in a cold and dry climate where primary production, including that of wood and leaves, is less than in the wet, temperate climate of the montane forest in the Erlenbach catchment. Litterfall significantly contributes to CPOM loads (Findlay et al., 1997). For the Erlenbach, a litterfall rate of 0.37 kg CPOM per m^2 and year is converted from the 0.18 kgC/ m^2 /yr reported by Turowski et al. (2016) and assuming a 48% carbon content for litterfall. Only half the litterfall rate is likely for the two high-elevation Rocky Mountain streams (0.125 to 0.2 kg/ m^2 /yr (Fahey, 1983; Bradford et al., 2010). Hillslope erosion rates also play a role as shown by Galy et al. (2015) who established a positive relation between fine carbon export and erosion rates. A similar relation can be expected for CPOM, because organic matter is also

supplied to the stream by surface wash or processes of hillslope erosion. Hillslopes are steep and unstable at the Erlenbach (Schuerch et al., 2006). Those conditions facilitate high physical erosion rates (cf. Turowski et al., 2009) and transfer organic-rich soil, duff, wood pieces, as well as logs and living trees into the stream (Jochner et al., 2015). Also, the drainage density for the forested watershed area is 5.7 km/km² (estimated from Fig. 1 in Jochner et al., 2015) at the Erlenbach, as opposed to 1.1 and 1.2 km/km² for the two Rocky Mountain streams (Table 1), and that increases the opportunity for fluvial export, and hence CPOM transport rates, at the Erlenbach. Finally, the amount of large woody debris (LWD) in the channel can affect the magnitude of CPOM transport rates, apart from hysteresis effects of CPOM transport rates caused by storage and release of CPOM around log jams (Section 5.2.2).

Prerequisites for a notable contribution of large woody debris (LWD) to CPOM are a high wood loading from which smaller logs may float downstream as part of CPOM as well as high gravel-cobble transport rates to grind down the wood, because generally, the rate at which LWD is worn into CPOM is slow (Bilby, 2003). Wohl and Goode (2008) report a relatively high wood loading of 9.1 m³/100 m averaged over a 47 m reach of the Rocky Mountain East St. Louis Creek. Similarly, a loading of 7.9 m³ wood/100 m stream averaged over a 320 m long reach that harbors nine logjams can be computed for the Swiss Erlenbach (Jochner et al., 2015), but within individual log jams, wood concentrations ranged from 14 to 98 m³ wood/100 m. Note though, that wood loading is rarely reported in its longitudinal variability for an entire stream system. Presumably, tree trunks supplied to the stream deteriorate faster into CPOM-size particles in the wet and temperate climate of the Swiss Erlenbach than the cold and dry climate of the Rocky Mountain streams. Furthermore, compared to the stable step-pool and plane-bed morphologies of the Rocky Mountain study streams, the Erlenbach torrent with its highly mobile bed and hillslopes has considerably higher gravel and cobble bedload transport rates, and those bedload impacts help to grind down logs into mobile CPOM particles. Hence, a smaller contribution of wood pieces to CPOM sized particles in the Rocky Mountain streams would further explain the lower CPOM

transport rates there. Comminution into particles sizes finer than CPOM as well as biological consumption—especially during lengthy CPOM storage times—decrease the amount of CPOM supply, but arguments whether those processes effect CPOM transport rates more in the Rocky Mountain or the Swiss stream could be made either way.

5.3.3 Variability in annual CPOM loads and yields among streams

While suitably measured CPOM transport relations appear to be only moderately variably among high elevation mountain streams in mostly coniferous watersheds, a comparison of annual CPOM loads among studied streams face additional uncertainties: There are methodological differences in the computation of annual load, and the number of measured high flow years as well as the relative magnitude of events included in the computation differ among studies, as is known from sediment transport studies.

Even more uncertainty occurs when comparing CPOM loads that are normalized by basin area size to become CPOM yield. In contrast to suspended sediment studies, basin area is not a meaningful parameter to characterize CPOM supply and delivery, considering that only a portion of the watershed area supplies CPOM to the channel. A constraint to the forested portion of the watershed is prudent, as evidenced by the two Rocky Mountain streams that have similar CPOM yields for the forested, but not for the entire watershed area (Table 5). However, in much of the forested catchment area in the two Rocky Mountain study streams, connectivity of hillslopes to the channel is limited to rarely occurring extreme rainfall events and offers little opportunity for much of the litter fall and tree throw material to reach the fluvial system. The 70-ha Erlenbach catchment, by contrast, is very well connected to the stream, with unstable hillslopes, high drainage density, and frequently occurring strong rainfall events. Considering the wide differences in hillslope-channel connectivity among watersheds, attribution of

CPOM export to those portions of the watershed that most actively contribute to the CPOM supply is more meaningful. Those areas are the seams along both channel banks of the fluvial system including the channel surface area if there is canopy closure. The width of CPOM-contributing bank seams may vary within and among streams depending on the degree of connectivity; As a preliminary proxy and to demonstrate the effect, the width was set arbitrarily to 25 m along both banks within the forested part of the watershed. Normalizing annual CPOM load by those channel seams reduces the difference in CPOM yields between the Rocky Mountain study streams and the Erlenbach to factors of 4 and 6 (Table 5), as opposed to the 20- and 30-fold difference in CPOM yields from the entire and the forested watershed areas, respectively (Table 5). Those 4- to 6-fold differences in CPOM yields (attributed to the area of channel plus seams) are similar to the difference in CPOM transport relations among the three streams (Fig. 10b). Similarly, CPOM yields attributed to the channel plus seams differ less among the three streams than CPOM yields attributed to the channel bed area.

6. Conclusions

Bedload traps enable a fairly representative field sampling of CPOM transport in mountain streams that are wadeable at high flows. Sampled CPOM transport rates may need to be adjusted to compensate for CPOM transport overtopping the traps and for overfilling the nets. The 3.6-mm mesh width does not seem to hinder the collection of slender conifer needles but allows small spherical particles to pass. Branches and logs cannot be collected in the bedload traps; they need to be sampled separately in high flow years and factored into the CPOM transport rate. Since gravel bedload and CPOM are jointly transported and captured in the sampler, it makes sense to combine field projects of bedload and CPOM sampling, as suggested by Beschta (1983).

Hysteresis in CPOM transport rates is pronounced, and this variability requires intensive sampling for accurately computing CPOM export from field samples. Sampling to obtain a time series and applying a summation approach is recommended, especially during the 1st rising limb of flow. The hysteresis patterns identified in the two study streams are considered representative for periods of relative channel and watershed stability, and those patterns can aid in supplementing field data to create a time series of CPOM transport rates in poorly sampled streams.

CPOM transport relations with unit discharge q appear to be relatively similar among steep mountain streams with mainly coniferous watersheds, and differences seem qualitatively attributable to various factors (e.g., litterfall rates, wood loading, hillslope-channel connectivity and drainage density, comminution of litter and wood into particles of CPOM sizes or smaller, as well as biological consumption. A rough estimate of a CPOM transport relation for an unsampled steep mountain stream in a coniferous subalpine and montane forest may be obtained by using the three sampled CPOM transport relations as a template and adjusting an unsampled transport relation by considering the stream's characteristics of CPOM supply, delivery, and transport dynamics.

The two Rocky Mountain streams had CPOM loads of 3.6 and 3.2 t/yr in the low flow study years, CPOM yields of 2.7 and 4.0 kg/ha/yr, and almost identical CPOM yields of 6.6 and 6.5 kg/ha/yr for the forested watershed portion. CPOM exports should represent long-term values, hence exports measured in a year with a low or high runoff require adjustments. Decadal average values for the two study streams were estimated as 11.3 and 10.2 t/yr for CPOM loads, 8.6 and 12.6 kg/ha/yr for CPOM yields, and close to 21 kg/ha/yr for the forested watershed part.

Analogous to suspended sediment loads, CPOM exports are typically compared among streams by normalizing annual CPOM loads by the entire (or the forested) basin area. Considering that large parts of a forested watershed may contribute very little to CPOM export, a more meaningful way to compare CPOM yields among steep mountain streams with coniferous watersheds may be to normalize annual CPOM loads by the area of seams along both stream banks together with the stream surface area.

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Figure captions

Fig. 1: Upstream views towards the Little Granite Creek study site with bedload traps installed (a). The East St. Louis Creek study site is located about 5 m downstream from the photo point (b).

Fig. 2: Bedload traps installed at East St. Louis Cr. (a); Retying the net after emptying the contents into buckets (b).

Fig. 3: Peakflow portion of the annual hydrograph (blue line) with measured CPOM transport rates (red open dots) and the interpolated continuous record of CPOM transport rates (red line) at Little Granite Creek (a) and East St. Louis Creek (b). Note different scales of plots.

Fig. 4: CPOM sample collected in a 5-gallon (18.9 liter) buckets at high flow in one of traps at Little Granite Creek (a) and at East St. Louis Creek (b). Detail of CPOM sample from Little Granite Creek (c).

Fig. 5: Sketches illustrating the interplay between vertical profiles of C_{CPOM} , v , and Q_{CPOM} . Flow direction is left to right. A downward increasing trend of C_{CPOM} causes a vertically approximately even Q_{CPOM} profile (a). With a vertically even distribution of C_{CPOM} , Q_{CPOM} is highest near the stream surface (b). A downward increasing trend of C_{CPOM} together with high near-surface concentration causes a slight increase of the Q_{CPOM} trend toward the top of the water column.

Fig. 6: Sketch indicating low to moderate flow condition in which bedload traps are not overtopped (a) and moderate to high flow conditions that causes overtopping by flow (b). Flow direction is left to right.

Fig. 7: Relation between Q_{CPOM} collected over 10 and 60 minutes at the same flows.

Fig. 8: Relations of CPOM transport rates vs. discharge for seasonal rising and falling limbs of flow at Little Granite Creek (a) and East St. Louis Creek (b). All p -values are < 0.0001 . Gray dashed line indicates relation for all data. Note different plot scales for (a) and (b).

Fig. 9: Similar hysteresis patterns in CPOM transport rates collected over the snowmelt high flow seasons in East St. Louis Creek (a) and Little Granite Creek (b). Q_{CPOM} ranges within the wide, top band (light gray) on the 1st rising limb, remains within the central band (middle gray) for the 1st falling and the 2nd rising limb, and drops to a lowest band (dark gray) on the 2nd falling limb.

Fig. 10: Transport relations of Q_{CPOM} vs. discharge Q (a) and unit discharge $q = Q/w$ (b) for the two Rocky Mountain streams compared to the Swiss Erlenbach torrent. The three color-coded bars on the bottom of panel (b) indicate the range of 10 to 100% of bankfull flow for each stream.

Figure 1

Fig. 1a and b

Figure 2

Fig. 2 a and b

Figure 3

Fig. 3 a and b

Figure 4

Fig. 4 a-c

Figure 5

Fig. 5 a - c

Figure 6

Fig. 6

Figure 7

Fig. 7

Figure 8

Fig. 8 a and b

Figure 9

Fig. 9 a and b

Figure 10

Fig. 10 a and b

Table 1

Table 1: Study site and basin characteristics for the two study streams.

	Little Granite Creek	East St. Louis Creek
Study site locations	Gros Ventre Range, 31 km SE of Jackson Hole, WY	Fraser Experimental Forest, 71 km NW of Denver, CO
Site coordinates	43°19'17.40"N; 110° 30'41.77"E	39°53'12.97"N; 105°52'38.42"W
Flow direction: headwaters; main stem	SW; SE	NW; N
Min. and max. basin elevations (m)	2,030 to 3,220	2,889 to 3,890
Drainage basin area (km ²)	13.09	8.03
% unforested ¹⁾	38 above treeline	33 above tree line + 5 too dry
% partially forested, open canopy ^{1, 2)}	41	-
% fully forested, (near) closed canopy ¹⁾	21	62
Stream gradient (m/m) at site, over reach	0.012, 0.018	0.03, 0.093
Stream width at study site (m)	5.0	3.5
¹⁾ Stream length incl. tributaries in fully forested watershed part (km)	14.5	10
Drainage density (km/km ²)	1.11	1.25
Reach stream morphology	plane-bed; forced pool-riffle seq.	step-pool; occ. forced pool-riffle
Bed surface D_{16} , D_{50} , and D_{84} sizes (mm)	23, 67, 138	15, 108, 258
Bankfull flow (m ³ /s)	2.83	0.764
Main lithology	sandstone, shale, limestone, granite	granite and schist

¹⁾ From Google Earth images in a scale of approximately 1:22,000.

²⁾ individual trees or tree groups discernible.

Table 2

Table 2: CPOM transport rates and loads for hydrograph portions at Little Granite Creek in 2002.

Time period	Hydrograph portion	Flow range (m ³ /s)	No. of days	Range of transport rates (g/min)	Seasonal, ann., and decadal load (t)	% of annual load
April 18 - May 12	prior to high flow	0.08-0.34	24	0.001 – 1.5 ¹⁾	0.013	0.4
May 12 - June 14	high flow	0.25-3.26	33	0.8 – 1458 ²⁾	3.45	96.6
June 14 - July 11	falling limb	0.29-1.17	27	0.06 – 13 ³⁾	0.101	2.8
July 12 - Sept 30	late summer low Q	0.15-0.29 est.	80	0.05 ³⁾	0.006	0.2
Oct 1 – April 17	base flow	0.09-0.15 est.	201	0	0	0
Annual load (t)	entire year		365		3.57	100
Ann. load (t/yr) adj. to decadal average	About 10 years				11.3	≅ 300

¹⁾ Extrapolated from rating curve for first rising limb.

²⁾ Based on intensive sampling that facilitated using a summation approach.

³⁾ Extrapolated from second falling limb.

Table 3

Table 3: CPOM loads for various hydrograph parts at East St. Louis Creek in 2001 and for a year with a simulated hydrograph reaching the bankfull level.

Time period	Hydrograph portion	Days	Flow range (m ³ /s)		Range of transport rates (g/min)		Seasonal, annual, and decadal loads		% of annual load	
			2001	bf-year	2001	bf-year	2001	bf-yr.	2001	bf-yr.
May 15 - June 1	rising limb	16	0.18-0.51	0.18-0.74	0.05-79 ¹⁾	0.05-1102 ¹⁾	0.0042	1.2	2.5	38
June 1 - June 17	High flow	12	0.34-0.53	0.53-0.76	1.6-99 ²⁾	15.5-1363 ²⁾	0.139	2.0	82	61
June 17 - July 15	falling limb	30	0.17-0.42	0.17-0.53	0.03-19 ¹⁾	0.01-15.5 ¹⁾	0.026	0.055	15	1.7
July 16 - Sept 30	late summer	77	0.044 - 0.19		~0-0.08 ³⁾	~0-0.08 ³⁾	0.00013		0.05	0.004
Oct 1 - May 14	base flow	230	0.028 - 0.044		≅ 0		≅ 0		≅ 0	
Annual load (t/yr)	entire year	365	0.028 - 0.76		0 – 1,363		0.169	3.24	100	
Ann. load (t/yr) adj. to decadal average	About 10 years						10.2		≅ 300	

¹⁾ Based on rating curve for 1st rising limb.

²⁾ Based on summation approach and intensive sampling.

³⁾ Based on rating curve for all data.

Table 4

Table 4: Comparison of CPOM yield among various streams with forested watersheds.

Location	Coweeta, NC, watersheds C53, C54, C55	Hubbard Brook, NH, watersheds W5, W6	Little Granite Cr., WY	East St. Louis ¹⁾ , Cr., CO	Juruena, Mato Grosso, Brazil	Erlenbach, Switzerland
Reference	Wallace et al. (1995)	Bilby & Likens (1980); Bilby (1981)	This study		Johnson et al. (2006)	Turowski et al. (2013, 2016)
Basin area (ha)	5.2 - 55	13 - 22	1309	803	1 - 2	70
Main forest type	deciduous	deciduous	coniferous		deciduous	coniferous
CPOM yield (kg/ha/yr)	0.14 - 1.2	7.1 - 15 ²⁾	2.7	4.0	3.7 ³⁾	
Adj. to decadal avg.	0.4 ⁴⁾	10 ⁴⁾	8.6 ⁵⁾	12.6 ⁵⁾		246 ⁶⁾
CPOM yield (kg/ha/yr) per forested basin area			6.6 ⁸⁾	6.5 ⁹⁾	3.7 ⁷⁾	
Adj. to decadal avg.	0.41 ⁷⁾	10 ⁷⁾	20.9 ⁵⁾	20.5 ⁵⁾		631 ¹⁰⁾

¹⁾ Est. for a year with bankfull flow.

²⁾ Based on 11 and 12 years prior to removal of debris dams.

³⁾ Based on a reported 3.5% portion of CPOC on total carbon export.

⁴⁾ Geometric mean of range given.

⁵⁾ Adjustment from a low flow year to represent a normal flow year, see discussion in Section 4.1.1.

⁶⁾ Based on 12.3 t carbon exported as CPOM per km²/year and a 50% carbon content of CPOM (Turowski et al., 2016).

⁷⁾ Assuming basins are fully forested.

⁸⁾ 21% basin area are fully forested; of the partially forested area (41%), half is counted to the fully forested area (=21% + 20.5% = 41.5% forested); 38% is above tree line or otherwise unforested.

⁹⁾ 62% basin area is fully forested; 33% above tree line and 5% otherwise sparsely forested.

¹⁰⁾ 39% of basin is forested, 61% is wetland and meadow (Turowski et al., 2016).

Table 5

Table 5: Comparison of CPOM loads and yields among Little Granite and East St. Louis Creek (Rocky Mountains) and the Erlenbach (Switzerland).

	Stream			Ratios		
	Little Granite Cr.	East St. Louis Cr.	Erlenbach	Little Granite Cr./ East St. Louis Cr.	Little Granite Cr./ Erlenbach	East St. Louis Cr./ Erlenbach
CPOM annual load (t/yr)	11.3 ¹⁾	10.2 ¹⁾	17.2 ²⁾	1.1	0.7	0.6
<u>Area (ha) of:</u>						
total watershed	1309	803	70	1.6	19	11
forested watershed	537 ³⁾	498 ⁴⁾	27 ⁵⁾	1.1	20	18
channel bed + 25-m seams	77 ⁶⁾	52 ⁷⁾	21 ⁸⁾	1.5	3.7	2.5
channel bed in forested WS	4.0	2.0	0.7	2.0	5.7	2.9
<u>CPOM annual yield (kg/ha/yr) of:</u>						
total watershed	8.6	13	246	0.68	0.04	0.05
forested watershed	21	20	630	1.03	0.03	0.03
channel bed + 25-m seams	148	196	825	0.75	0.18	0.24
channel bed in forested WS	2825	5100	24571	0.55	0.11	0.21

¹⁾ Adj. to reflect decadal averages.

²⁾ Based on carbon export of 12.3 t/km²/yr and 50% carbon content of CPOM reported by Turowski et al. (2016).

³⁾ 21% fully forested and 41% partially (approx. 50% forested) → 41% forested.

⁴⁾ 62% forested.

⁵⁾ 39% forested.

⁶⁾ See Table 1 for stream length. Average stream width of 2 m for tributaries and 5 m for the main stem.

⁷⁾ See Table 1 for stream length. Average stream width of 1.5 m for tributaries and 2.5 m for the main stem.

⁸⁾ Stream length estimated from map with scale of 1:26,700 (Fig. 1 in Jochner et al. , 2015), and widths estimates of 1.5 m for tributaries and 3.5 m for the main stem.