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Decadal carbon discharge by a mountain stream is dominated by coarse organic matter

Jens M. Turowski[1]*, Robert G. Hilton[2], Robert Sparkes[3,4]
[1]Swiss Federal Research Institute WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland
[2]Department of Geography, Durham University, Science Laboratories, South Road, Durham DH1 3LE, UK
[3]Department of Materials Science and Metallurgy, University of Cambridge, 27 Charles Babbage Road, Cambridge CB3 0FS, UK
[4]School of Earth Atmospheric and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester M13 9PL, UK

ABSTRACT

Rapid erosion in mountain forests results in high rates of biospheric particulate organic carbon (POC) export by rivers, which can contribute to atmospheric carbon dioxide drawdown. However, coarse POC (CPOC) carried by particles >~1 mm is rarely quantified. In a forested pre-Alpine catchment, we measured CPOC transport rates and found that they increase more rapidly with water discharge than fine POC (<1 mm) and dissolved organic carbon (DOC). As a result, decadal estimates of CPOC yield of 12.3 ± 1.9 t C km^{-2} yr^{-1} are higher than for fine POC and DOC, even when excluding 4 extreme flood events. When including these floods, CPOC dominates organic carbon discharge (~80%). Most CPOC (69%) was water logged and denser than water, suggesting that CPOC has the potential to contribute to long-term sedimentary burial. Global fluxes remain poorly constrained, but if the transport behavior of CPOC shown here is common to other mountain streams and rivers, then neglecting CPOC discharge could lead to a large underestimation of the global transfer of biospheric POC from land to ocean.

INTRODUCTION

Erosion of particulate organic carbon (POC) from the terrestrial biosphere and its transport by rivers redistributes nutrients and can contribute to atmospheric carbon dioxide drawdown (Berner, 1982; Stallard, 1998; Battin et al., 2008; Galy et al., 2015). High rates of physical erosion in mountain catchments result in elevated rates of fine POC discharge (FPOC, particles >0.2–0.7 μm and <1 mm), with biospheric FPOC (FPOC$_{\text{biosphere}}$) yields >10 t C km^{-2} yr^{-1} (Hilton et al., 2012; Goñi et al., 2013; Smith et al., 2013; Galy et al., 2015). As a result, mountain rivers can contribute significant amounts of FPOC$_{\text{biosphere}}$ to large rivers, lakes, and the oceans (Stallard, 1998; Hilton et al., 2012; Galy et al., 2015). This carbon, recently derived from atmospheric carbon dioxide via photosynthesis, is often transported along with large volumes of clastic sediment (Hilton et al., 2012). High sediment accumulation rates in depositional settings can increase the burial efficiency of POC$_{\text{biosphere}}$ and promote the drawdown of atmospheric CO$_2$ over geological time scales (Berner, 1982; Kao et al., 2014; Galy et al., 2015).

Despite this recognition, the organic carbon (OC) transported as coarse particulate organic matter (CPOM, particles >1 mm) remains poorly constrained, mainly because it is challenging to measure. CPOM can range in size from leaves to entire trees, and is not captured by typical river water sampling methods (e.g., Goñi et al., 2013; Smith et al., 2013; Hilton et al., 2015), while it is transported episodically during large floods when it is difficult to work in river channels (West et al., 2011; Wohl, 2013; Kramer and Wohl, 2014). CPOM also contributes to ecosystem functions because it typically contains ~50% carbon by weight and can form the basis of the food chain in many streams (Fisher and Likens, 1973). In addition to contributing to carbon and nutrient transfers in rivers, large wood, consisting of CPOM with lengths >1 m, can affect stream morphology and hydraulics, while providing shelter for in-stream fauna and affecting breeding grounds (Wohl, 2013).

A significant challenge remains to accurately measure coarse POC (CPOC) transport in rivers across the full size range of CPOM, while linking CPOC transfer to hydrodynamic conditions in rivers; only by doing so can CPOC yields (t C km^{-2} yr^{-1}) be accurately quantified. In addition, CPOC eroded from the biosphere is often thought to float (West et al., 2011), suggesting that it could be more susceptible to oxidation upon its delivery to floodplains (Fisher and Likens, 1973), lakes and reservoirs (Seo et al., 2008), and the oceans (West et al., 2011). However, water-logged woody debris, with a density higher than water, is a component of FPOC$_{\text{biosphere}}$ in large river systems (Bianchi et al., 2007; Hilton et al., 2015). The amount of water-logged CPOC discharged by mountain rivers remains unknown. Here we use detailed measurements of CPOM transport in the Erlenbach, a 0.7 km^2 catchment in the Swiss Prealps. Although small, the catchment has geomorphic, climatic, and ecological characteristics that are representative of forested mountain headwater streams in a temperate climate (Schleppi et al., 1999; Smith et al., 2013).

METHODS

The Erlenbach is a steep (11% slope) mountain stream with step-pool morphology and drains 0.7 km^2 in the Swiss Prealps (47.045707°N, 8.708844°E) (Fig. 1). The mean annual air temperature is ~4.5 °C and the mean annual precipi-

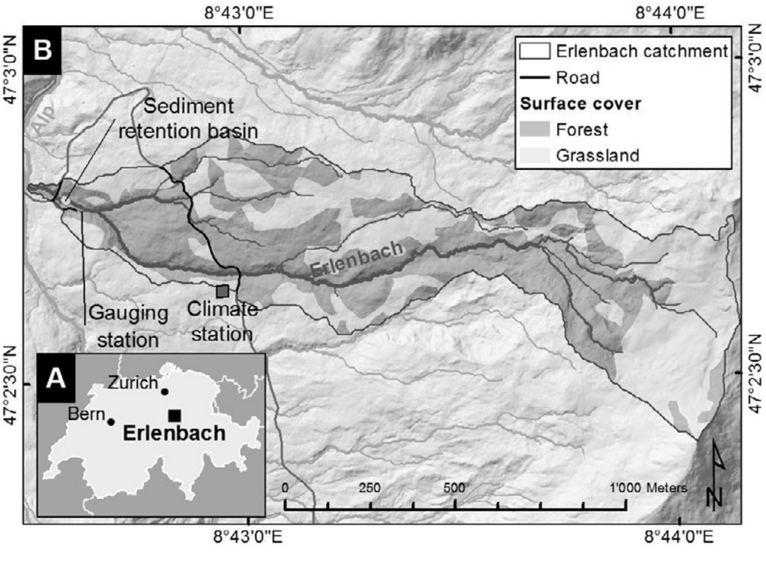

Figure 1. A: Location of the Erlenbach catchment in Switzerland. B: Map of the catchment.

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*Current address: Section 5.1 Geomorphology, Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg 14473 Potsdam, Germany; E-mail: turowski@gfz-potsdam.de.

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tation is ~2300 mm. Approximately 40% of the total catchment area is covered by alpine forest, mainly comprising Norway Spruce (*Picea abies*) and European Silver Fir (*Abies alba*) (Schleppi et al., 1999), and a small amount of logging has been done in the upper catchment over the past 10 yr. The remaining 60% of the catchment is covered by wetland and alpine meadows. A well-developed riparian zone is generally lacking and active landslide complexes along the channel lead to strong channel-hillslope coupling typical of many steep mountain catchments. Both DOC and FPOC fluxes have been previously determined (Hagedorn et al., 2000; Smith et al., 2013). The FPOC has been partitioned into that derived from the terrestrial biosphere ($FPOC_{biosphere}$) and that from rock-derived OC using stable carbon isotopes, nitrogen to carbon ratios, and radiocarbon (Smith et al., 2013).

We use CPOM data sampled with three different methods (see the GSA Data Repository[1]), each of which is suitable for a different water discharge range (Turowski et al., 2013). All sampling locations were within 30 m of a permanently installed gauge measuring water discharge (Q_w, L s^{-1}) at 10 min intervals (Rickenmann et al., 2012). At low Q_w (1 L s^{-1} to 1000 L s^{-1}; most samples <250 L s^{-1}), Bunte traps were used (Bunte et al., 2007). These are metal frames placed on the stream bed, to which a net with 6 mm meshing is attached. At intermediate Q_w (200 L s^{-1} to 1500 L s^{-1}; most samples >400 L s^{-1}) basket samplers were used (Rickenmann et al., 2012), consisting of metal cubes with 1 m edges and walls and floor made of metal mesh with 10 mm holes. The samplers automatically move into the flow when Q_w exceeds a predefined threshold value and when bedload transport is recorded. Both traps and baskets sample the entire flow depth with nearly 100% efficiency (Rickenmann et al., 2012; Turowski et al., 2013).

Woody material in the basket and trap samples was separated from clastic material in the field and weighed. Basket samples from A.D. 2011 to 2013 were separated into floating and sinking fractions in the field by dropping them into a water-filled bucket. Subsequently, the material was dried for 24 h at 80 °C, and the dry mass was obtained.

The diameter and length of large woody debris trapped in a retention basin after two extreme events (1995, 2010) complement the data at high Q_w (>5000 L s^{-1}). Masses were calculated assuming a cylindrical shape and a dry density of 410 kg/m^3, which is typical for the Norway Spruce (*Picea Abies*) that is common in the catchment. The three methods were made comparable by using distributions of particle masses (Turowski et al., 2013). CPOC was calculated from CPOM using the mean OC content of 47.8% ± 3.8% (±standard deviation) measured from 37 randomly drawn subsamples.

RESULTS

The transport rate of CPOC (kg C s^{-1}) was positively correlated with Q_w and well described by a power law rating curve ($r^2 = 0.87$; Fig. 2A). CPOC transport increases much more rapidly with increasing Q_w (rating curve exponent $\beta = 4.14 \pm 0.19$) than DOC ($r^2 = 0.98$, $\beta = 1.17 \pm 0.04$) and $FPOC_{biosphere}$ ($r^2 = 0.88$, $\beta = 1.90 \pm 0.10$). The data confirm that high river power is needed to mobilize and transport CPOC (West et al., 2011; Wohl, 2013). The relationship is consistent with the difference between bedload and suspended load transport rates in the Erlenbach (cf. Turowski et al., 2009; Smith et al., 2013), suggesting that CPOC is traveling as part of the bedload. This interpretation is supported by the observation that large fractions (mean 69%, median 78%) of the CPOM were water logged and denser than water, especially at high Q_w (Fig. 2B). Water logging likely occurs during storage of CPOM in log jams in the stream, or within saturated soil and litter on the hillslopes.

To estimate the decadal rate of CPOC discharge, we fitted a linear regression in double-logarithmic space to obtain a rating curve. The data points obtained from the retention basin material were not included in the regression, but are close to the rating curve at high Q_w. We used additional data from 2013, which resulted in a different rating curve than previously published (cf. Turowski et al., 2013). The rating curve was integrated over 31 yr of Q_w measurements. During this period, 4 exceptional flood events affected the catchment (Turowski et al., 2009), with peak Q_w >9000 L s^{-1} and return periods >20 yr. Not accounting for these 4 floods, the background CPOC yield was 12.3 ± 1.9 t C km^{-2} yr^{-1}. Uncertainties were derived from analytical errors of the rating curve fits. The exceptional floods delivered between 331 and 1066 t C km^{-2}, with an average of 585 t C km^{-2}. These values are lower than the 6300–19,100 t C km^{-2} of large wood carbon (LWC) delivered to the ocean during typhoon Morakot in Taiwan (West et al., 2011), but higher than the 10–24 t C km^{-2} of LWC delivered from the upper Rio Chagres, Panama, in a rain storm (Wohl and Ogden, 2013). In total, the 4 floods delivered 2338 ± 1609 t C km^{-2}, or 75.4 ± 51.9 t C km^{-2} yr^{-1}. When added to the background rate,

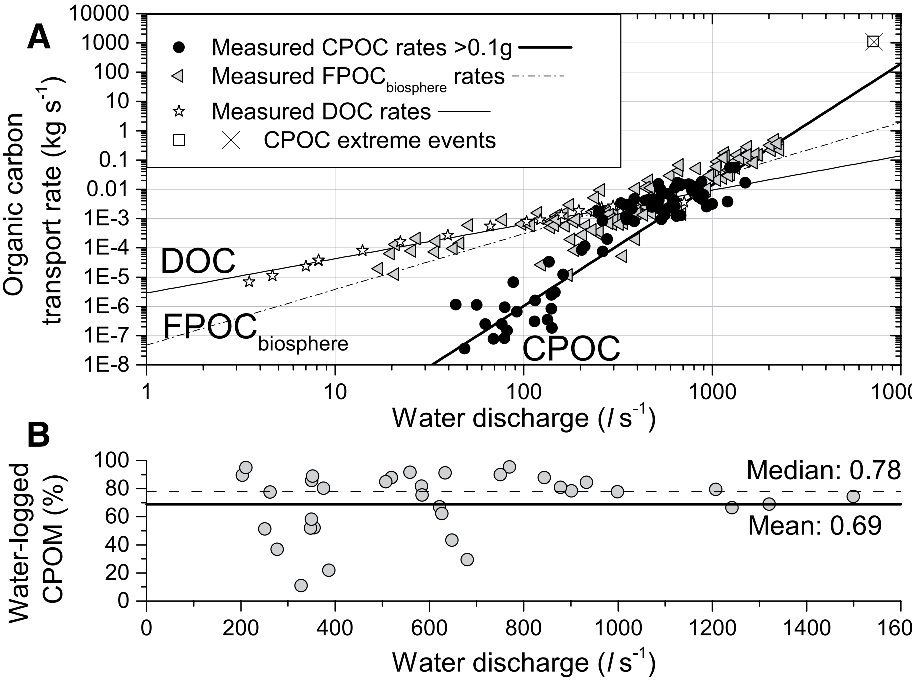

Figure 2. A: Coarse particulate organic carbon (CPOC) transport rate (kg C s^{-1}) as a function of water discharge (L s^{-1}) for the Erlenbach study catchment, Switzerland. Also shown are published measurements of dissolved organic carbon (DOC) (Hagedorn et al., 2000) and fine biospheric particulate organic carbon ($FPOC_{biosphere}$) transfer (Smith et al., 2013). Data are fit with power law rating curves for CPOC (thick solid line, exponent $\beta = 4.14 \pm 0.19$), $FPOC_{biosphere}$ (dashed line, $\beta = 1.90 \pm 0.10$), and DOC (fine solid line, $\beta = 1.17 \pm 0.04$). CPOC data from extreme events in A.D. 1995 and 2010 (box, cross) support the rating curve fit. B: Percent of water-logged coarse particulate organic matter (CPOM) at the time of collection. Mean (69%) and median (78%) of 35 basket samples are indicated by the solid and the dashed line, respectively. Low values at water discharges <600 L s^{-1} arose from autumn samples with small absolute mass consisting mainly of fresh leaves. Summed over all samples, water-logged CPOM contributed 76% to the total dry mass.

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[1] GSA Data Repository item 2016007, additional method information and Figures DR1–DR3, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

the average CPOC discharge estimate is 87.7 ± 51.9 t C km^{-2} yr^{-1}. Exceptional flood events appear to be even more important for CPOC than for FPOC$_{\text{biosphere}}$ (Hilton et al., 2012), which results from the steep relationship between CPOC transport rate and Q_w (Fig. 2A; Fig. DR1 in the Data Repository).

The background CPOC yield (12.3 ± 1.9 t C km^{-2} yr^{-1}) from the Erlenbach is a significant catchment-scale carbon transfer (Hilton et al., 2012; Galy et al., 2015) and on its own is comparable to the upper range of estimates of FPOC$_{\text{biosphere}}$ yields from temperate and tropical active mountain belts (Fig. 3). Other carbon transfers from the Erlenbach, obtained using the same methods on previously collected data (Hagedorn et al., 2000; Smith et al., 2013), are lower than CPOC transfer, with a DOC yield of 11.3 ± 0.0 Mg C km^{-2} yr^{-1}, and an FPOC$_{\text{biosphere}}$ yield of 10.7 ± 0.1 Mg C km^{-2} yr^{-1}. The background CPOC transfer thus represents ~36% of the decadal biospheric OC discharge by this catchment. Inclusion of the exceptional events raises CPOC transfer to as much as ~80% of the total OC (TOC) discharge (Fig. 3). We can assess the sustainability of OC export by comparing it to the net primary production (NPP) of ~740 Mg C km^{-2} yr^{-1} in the Erlenbach catchment (see the Data Repository). The background rate of CPOC discharge is ~1.7% of this NPP and is sustainable, in agreement with a global compilation of river FPOC$_{\text{biosphere}}$ yields (Galy et al., 2015). However, extreme events may severely deplete the biosphere stock of carbon. The CPOC discharge during a single event appears to have the potential to exceed the catchment's yearly production; our data suggest that on decadal time scales, exceptional events discharge ~10% of the NPP.

DISCUSSION

The contribution of CPOC to carbon discharge by rivers is not typically quantified, and a direct comparison with data from other catchments remains challenging. Notwithstanding, it has been calculated that LWC alone contributes at least 10% and as much as 35% of the total carbon yields in mountain rivers with catchment areas as large as 2000 km^2 (Fig. DR2) (Seo et al., 2008). CPOM particles smaller than large wood to sizes of 1 mm were not considered in that study, but dominate CPOC in the Erlenbach (cf. Turowski et al., 2013). Based on the Erlenbach's size, its FPOC$_{\text{biophere}}$ and LWC yields are similar to those observed in other mountain regions in the world (Fig. DR2). FPOC$_{\text{biosphere}}$ yields are known to be strongly linked to physical erosion rate (Fig. 3) (Galy et al., 2015), and high yields are observed in active mountain belts in temperate and tropical settings (Hilton et al., 2012). In accord with this, estimates of LWC transfer in Taiwanese catchments are larger than for the Erlenbach (West et al., 2011). Therefore, we propose that the often unmeasured CPOC fraction is a significant component of POC$_{\text{biosphere}}$ export from forested mountain catchments.

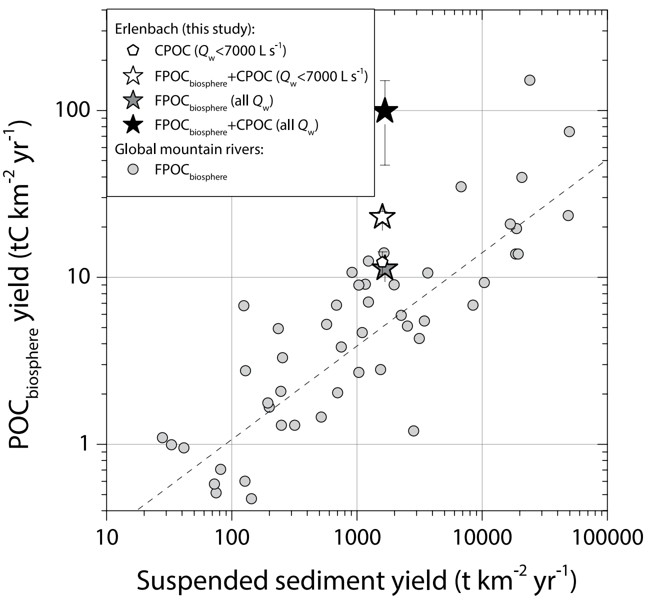

Figure 3. Literature data of biospheric particulate organic carbon (POC$_{\text{biosphere}}$) yield (t C km^{-2} yr^{-1}) plotted against suspended sediment yield (t km^{-2} yr^{-1}) for global rivers with fitted relationship (dashed line) (Galy et al., 2015) (Q_w— water discharge). The Erlenbach (Switzerland) catchment does not show exceptional fine POC$_{\text{biosphere}}$ (FPOC$_{\text{biosphere}}$) yields for its suspended sediment yield. Inclusion of coarse POC (CPOC) for the Erlenbach, not available for the other catchments, increases carbon export by an order of magnitude (black and white stars).

To make a tentative first assessment of the global significance of CPOC transport, we assume that the Erlenbach catchment is representative for temperate mountain forests, which cover a total area of 1.2 × 10^6 km^2 worldwide (Sands, 2005). While the climatic, geomorphic, and ecological characteristics of the Erlenbach support that assumption, its physical erosion rate is high (Fig. 3). Without more measurements of CPOC transport (Fig. 1) and estimation of CPOC yields (Fig. 3), a global CPOC discharge estimate remains poorly constrained. Based on the Erlenbach background CPOC yield over 31 yr (12.3 ± 1.9 t C km^{-2} yr^{-1}), the global CPOC discharge from temperate mountain forest catchments could be ~15 Mt C yr^{-1}. This is ~10% of the recent estimate of global FPOC$_{\text{biosphere}}$ discharge to the oceans by rivers of 157 +74/–50 Mt C yr^{-1} (Galy et al., 2015). If extreme floods are included, CPOC discharge from temperate mountain forests could be even higher (Fig. 3). Global CPOC discharge would further increase if boreal, subtropical, and tropical mountain forests were considered. We are aware that these estimates are based on extrapolation from a very small continental area and absolute flux has large uncertainty. Nevertheless, the magnitude of the estimate demonstrates the need to better quantify CPOC transfer rates in mountain rivers and track its conveyance through large river systems.

Little is known about the onward fate and routing of CPOC through large rivers. On average ~69% of the CPOM transported by the Erlenbach was water logged, with a density greater than water (Fig. 2B). If this observation applies to other temperate streams where channel morphology can promote transient storage of CPOM, sampling with drift nets may have missed large fractions of CPOM traveling near the stream bed. Perhaps more important, water-logged CPOM may have a different fate in fluvial networks than if it were to float. During transport in steep channels, water-logged CPOM may be ground by gravel bedload, reducing its size. The size reduction of CPOM by bedload grinding is poorly understood, but the observed magnitude of the CPOC flux means it could be an important in-stream source of FPOC$_{\text{biosphere}}$ (Hilton et al., 2012).

Furthermore, a high density of CPOM may promote its burial potential in sedimentary basins. If water-logged CPOM is delivered to depositional environments as part of the bedload it is more likely to rapidly accumulate in sedimentary deposits. Observations of large terrestrial organic debris in deep-sea turbidites in Indonesia (Saller et al., 2006), woody clasts and plant debris in modern deep-sea sediments offshore Taiwan (Kao et al., 2014), and mountain rivers draining the west coast of the United States (Leithold and Hope, 1999) all suggest that CPOC can be delivered to deep-marine settings. We substantiate these arguments by estimating the contribution of CPOC to TOC in exhumed turbidite sequences in the Apennines, Italy (see the Data Repository). Despite estimated transport distances of as much as 300 km offshore, CPOC was buried and preserved for 14 m.y. and represents ~10% of the TOC. Water-logged woody debris can be delivered by mountain rivers as CPOC (Fig. 2B), and its presence may enhance the efficiency of carbon burial and associated atmospheric CO$_2$ sequestration by erosion of mountain belts (Kao et al., 2014; Galy et al., 2015).

CONCLUSIONS

CPOC is the dominant form of OC discharge by the Erlenbach over decadal time scales, increasing the carbon loss from the biosphere by ~250% over DOC and $FPOC_{biosphere}$. The majority of CPOC may be transported in water-logged CPOM as part of the bedload. Our observations provide new impetus to study the production, transfer, and routing of CPOC from mountain headwaters, and subsequently through large river systems to fully assess the net impact of erosion on the global carbon cycle (Battin et al., 2008; Hilton et al., 2012, 2015; Galy et al., 2015). Due to anthropogenic CO_2 emissions and global warming, extreme precipitation events may become more frequent (Rajczak et al., 2013), causing an increased number of extreme floods. CPOC transport exhibits a much stronger dependency on water discharge than FPOC and DOC transport (Fig. 1), and could therefore become more important for carbon budgets of mountain streams in the coming decades. This may have implications for forest management, food availability in stream ecosystems, and carbon mobilization by erosion of the terrestrial biosphere.

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Jens M. Turowski(1,2), Robert G. Hilton(3), Robert Sparkes(4)
(1) Swiss Federal Research Institute WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland
(2) Now at: Section 5.1 Geomorphology, Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg 14473 Potsdam, Germany, turowski@gfz-potsdam.de
(3) Department of Geography, Durham University, Science Laboratories, South Road, Durham, DH1 3LE, UK, r.g.hilton@durham.ac.uk
(4) School of Earth Atmospheric and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester, M13 9PL, UK, robert.sparkes@manchester.ac.uk

Supplementary Material

The Erlenbach catchment observatory

The Erlenbach drains 0.7 km^2 in the Swiss Prealps (LAT47.045707°, LON8.708844°) and hosts observatories on hydrology, sediment transport, channel dynamics, and forest ecology (Schleppi et al. 1999, Hegg et al. 2006, Turowski et al. 2009, Molnar et al. 2010, Rickenmann et al. 2012, Turowski et al. 2013b). The main observation site features two water gauging stations upstream and downstream of a sediment retention basin and has been described in detail elsewhere (Turowski et al. 2009; Rickenmann et al. 2012; Beer et al. 2015). There, further infrastructure for the observations of bedload transport and stream chemistry is available. The Erlenbach lies in a region with wet temperate climate, with a mean annual air temperature of ~4.5°C and mean annual precipitation of ~2300 mm. Approximately 40% of the total catchment area is covered by alpine forest, mainly comprising Norway Spruce (*Picea abies*) and European Silver Fir (*Abies alba*) (Schleppi et al. 1999). A small amount of logging has been done in the upper catchment over the past ten years. The remaining 60% of the catchment is covered by wetland and alpine meadows. A well-developed riparian zone is generally lacking and active landslide complexes along the channel lead to strong channel-hillslope coupling typical of many steep mountain catchments (Schuerch et al., 2006). Due to the wet climate, forest fires do not generally occur in the region. The last major storm in the region that caused wide-spread tree felling by wind was Lothar in 1999, which, however, did not significantly affect the Erlenbach catchment. The channel has a steep bed with on average 18% channel bed slope (11% at the observation site), and comprises a step-pool morphology (Molnar et al. 2010). Log jams are common, with an average density of 2.8 per 100m channel length (Jochner et al. 2015). Log jams are important storage sites for organic material, both for larger material in the jams itself, and smaller material in the sediment wedges upstream of them. Log jam destruction during high flows is at least partly responsible for the steep rating curve relation between CPOM transport and water discharge (Jochner et al. 2015).

CPOM sampling

The sampling methods have been described in detail by Turowski et al. (2013a). In summary, Bunte traps (Bunte et al. 2007) were used at low water discharge, as long as the stream wadeable. Bunte traps consist of a metal frame placed on a ground plate fixed on the stream bed with a net with a mesh size of 6mm attached. We sampled at three locations within a few meters of each other: at the crown and the foot off a step, using a single trap, and at the end of a pool, using two traps placed along the cross section. At the crown and the foot of the step, the single trap sampled the entire flow width and depth. At the end of the pool, the measurements of the two traps were interpolated to the unmeasured parts of the cross section as described by Turowski et al. (2013a). The measured CPOM fluxes as a function of water discharge are consistent for these three locations (Turowski et al. 2013a).

At intermediate water discharges, we used basket samplers (Rickenmann et al. 2012; Beer et al. 2015). The baskets consist of metal cubes with 1m edge length, where sides and bottom are made of metal grid with 1cm holes, while the top is open. They are mounted on a rail on a check dam and automatically move into the flow when pre-set discharge or sediment transport thresholds are exceeded. At the discharges they were employed, the basket captures the entire flow width, and the sample with near 100% efficiency (Rickenmann et al. 2012), and the main error in flux measurements arises from the weighing of the material (Beer et al. 2015). In case of CPOM, dried masses were obtained to the nearest gram in the laboratory using a precision scale, and total errors are small.

The CPOM measurements using traps and baskets are supplemented with data of large wood caught in the outlet grid of the sediment retention basin after two of the four extreme events (1995, 2010).

All data were made comparable by extrapolating to a cut-off particle mass of 0.1g as described by Turowski et al. (2013a).

Calculation of the net primary productivity (NPP)

Net primary productivity (NPP) of 520 MgC yr^{-1} was calculated as the sum of 1.61 kgC $m^{-2}yr^{-1}$ wood production and 0.18 kgC $m^{-2}yr^{-1}$ litter fall in the forest (40% of the catchment area of 0.7 km^2) (Krause et al. 2013), 0.75 kgC $m^{-2}yr^{-1}$ grass production in the meadows (Providoli et al. 2005), and 0.42 kgC $m^{-2}yr^{-1}$ soil respiration for the entire catchment (Krause et al. 2013).

Turbidite deposits

Distal turbidite samples were collected using a coring drill-bit from a quarry above Lamoli village, Marche, Italy, (43.628°N, 12.246°E) and form part of the Marnoso Arenacea turbidite system (Amy and Talling 2006). This system comprises extremely large (120 km x 30 km) laterally-correlated turbidite units sourced from the southern flank of the Alps. An associated sedimentary log recorded sediment grain size and the visibility of CPOC (Figure DR3). The turbidite used in this study was identified as Bed 6 by Amy and Talling (2006), a 2.8m-thick event bed, six layers above the "Contessa" marker layer. CPOC was observed in some parts of the turbidite, present as elongate woody fibres with length 1-30 mm and aspect ratio 2:1 up to 10:1, as observed in modern turbidite deposits (Sparkes et al., 2015). CPOC was concentrated in a 30-40 cm thick silty layer between the lower sandy section and the turbidite mud cap, and sporadically present in the mud cap. Additional field observations of CPOC in the same turbidite layer were made 48 km north (44.004°N, 11.939°E) and 34 km south (43.372°N, 12.459°E) of this location, suggesting that the CPOC layer was laterally-pervasive throughout the turbidite (Sparkes 2012). Again there was a concentrated layer of CPOC between the sandy and muddy sections of the turbidite, with some CPOC present within the mud cap. Powdered, decarbonated samples were analyzed (Hilton et al. 2010), producing measurements of total OC (TOC), total Nitrogen (TN) and stable carbon and nitrogen isotopic ratios ($\delta^{13}C_{OC}$, $\delta^{15}N$) (Figure DR3; Sparkes 2012). An unmixing algorithm was applied to categorise OC as coming from terrestrial biomass ($OC_{terrbio}$), bedrock erosion and marine organic carbon. The algorithm used simultaneous equations to deconvolve the measured $\delta^{13}C_{OC}$, $\delta^{15}N$ and N/C values into defined endmembers, as described by Sparkes et al. (2015). $OC_{terrbio}$ values within the turbidite mud cap were uniform (0.19 ± 0.02 wt%C, n = 8), and significantly higher in the CPOC-rich layer (0.29 ± 0.04 wt%C, n = 3). $OC_{terrbio}$ was negligible in the sand layer (0.02 ± 0.03 wt%C, n = 9). The contribution of CPOC to the 2.8m-thick event turbidite sequence was estimated by assuming that some of the $OC_{terrbio}$ in the CPOC-rich layer was fine grained in analogy to the mud cap (0.19 ± 0.02 wt%C, n=8). The remaining $OC_{terrbio}$ (0.10 wt%) in the 30-40 cm thick silty layer was attributed to CPOC. The CPOC and non-CPOC $OC_{terrbio}$ concentrations were weighted by layer thickness and compared to the total $OC_{terrbio}$ measured in the turbidite section. Since there was a smaller, but non-zero, amount of CPOC in the mud cap, this produces a conservative estimate that by mass, the CPOC across the event represents 10% ± 4% of the total $OC_{terrbio}$ present in the turbidite deposit at this location. This value rose to 12% ± 6% when a slightly less conservative approach was taken, in which excess $OC_{terrbio}$ in the mud cap ($OC_{terrbio}$ values greater than 0.19 ± 0.02 wt%C) was also attributed to CPOC. Similar field observations of CPOC along the length of the turbidite suggest that the attribution of ≥10% of $OC_{terrbio}$ to CPOC is representative of the turbidite as a whole.

Additional figures

This section includes three figures.

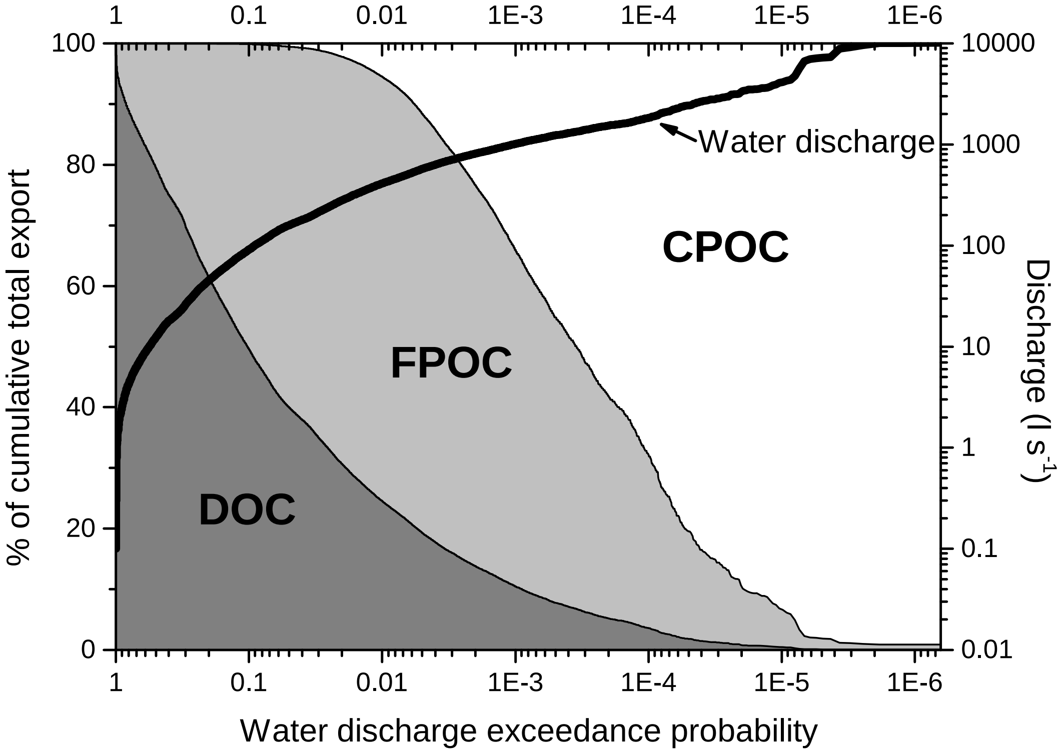

Fig. DR1: Partitioning of carbon export between dissolved organic carbon (DOC; dark grey), total fine particulate organic carbon (FPOC; light grey) and coarse particulate organic carbon (CPOC; white) for increasing discharges (thick black line). CPOC dominates carbon fluxes at high discharges.

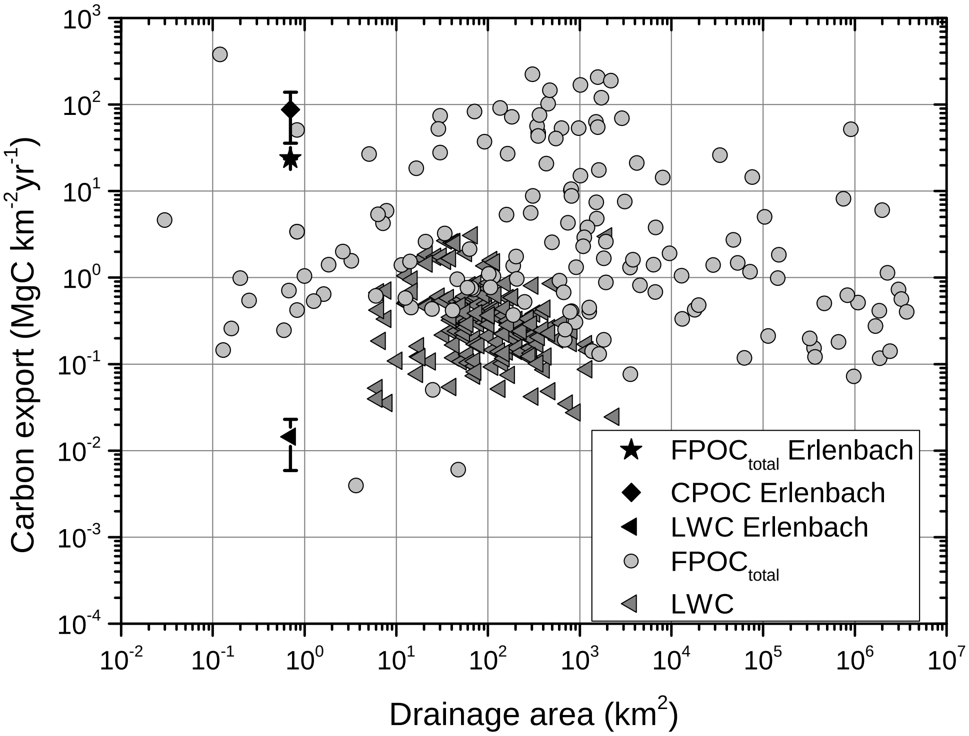

Fig. DR2: Total fine particulate organic carbon (FPOC$_{total}$) and large woody debris carbon (LWC) yields for catchments around the world. The Erlenbach does not carry exceptionally high carbon loads in comparison with other mountain rivers. FPOC$_{total}$ data comes from a recent compilation (Alvarez-Corbelas et al. 2012), complemented with additional values from mountain areas around the world (Hope et al. 1994, Bird et al. 1995, Kao et al. 1996, Lyons et al. 2002, Gomez et al. 2003, Sharma and Rai 2004, Carey et al. 2005, Coynel et al. 2005, Hilton et al. 2008b, Hilton et al. 2011, Hatten et al. 2012, Dhillon and Inamdar 2013, Goñi et al. 2013, Lloret et al. 2013). LWC data were taken from Seo et al. (2008).

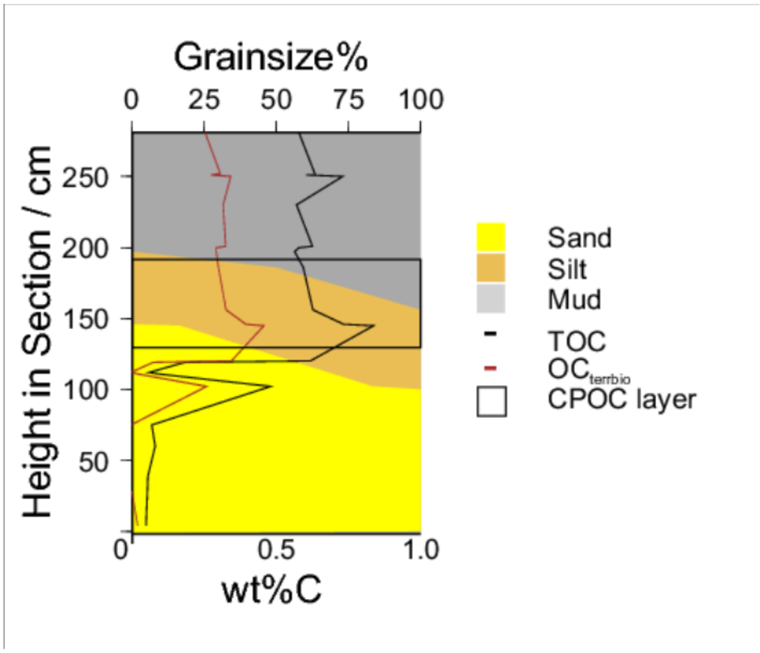

Fig. DR3: Sedimentary log of the turbidite section used to calculate the contribution of CPOC to offshore OC-rich deposits. Black line represents TOC measurements (wt%C units). Red line represents the wt%C attributed to $OC_{terrbio}$ at each sample location using the method of Sparkes et al. (2015). Sand, silt and mud layers are shown in yellow, orange and grey respectively. The section richest in CPOC is shown with a black outline.

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