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Runoff-driven export of particulate organic carbon from soil in temperate forested uplands

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ABSTRACT

We characterise the sources, pathways and export fluxes of particulate organic carbon (POC) in a headwater catchment in the Swiss Alps, where suspended sediment has a mean organic carbon concentration of 1.45% ± 0.06. By chemically fingerprinting this carbon and its potential sources using carbon and nitrogen elemental and isotopic compositions, we show that it derives from binary mixing between bedrock and modern biomass with a soil-like composition. The hillslope and channel are strongly coupled, allowing runoff to deliver recent organic carbon directly to the stream beyond a moderate discharge threshold. At higher flows, more biomass is mobilised and the fraction of modern carbon in the suspended load reaches 0.70, increased from 0.30 during background conditions. Significant amounts of non-fossil organic carbon are thus transferred from the hillslope without the need for extreme events such as landsliding. Precipitation is key: as soon as the rain stops, biomass supply ceases and fossil carbon again dominates. We use rating curves modelled using samples from five storm events integrated over 29-year discharge records to calculate long-term export fluxes of total POC and non-fossil POC from the catchment of 23.3 ± 5.8 and 14.0 ± 4.4 t km^{-2} yr^{-1} respectively. These yields are comparable to those from active mountain belts, yet the processes responsible are much more widely applicable. Such settings have the potential to play a significant role in the global drawdown of carbon dioxide via riverine biomass erosion, and their contribution to the global flux of POC to the ocean may be more important than previously thought.

1. Introduction

Export and deep marine burial of carbon from plants and soils, recently fixed from the atmosphere by photosynthesis, transfers carbon from the atmosphere into geological storage (e.g. Berner, 1982; France-Lanord and Derry, 1997). Previous work on carbon export from catchments has focused on active mountain belts because of their importance in the physical erosion budget (Milliman and Syvitski, 1992). For example, recent studies (Carey et al., 2005; Hilton et al., 2008a, 2008b; Lyons et al., 2002) suggest that storm-driven erosion of terrestrial biomass can effectively sequester carbon in tectonically and climatically extreme regimes, such as the active mountain belts of Taiwan and New Zealand. Deep-seated landslides and gully erosion are important in mobilising particulate organic carbon (POC) in extreme events in these environments (Hilton et al., 2008a; West et al., 2011). This POC consists of both modern POC from biomass and fossil POC from sedimentary bedrock. However, there are also indications that erosion processes associated with less intense runoff, driven directly by precipitation, may also be important, particularly in shifting the balance of POC carried in the suspended load towards non-fossil sources (Gomez et al., 2010; Hilton et al., 2012a, 2008b). While deep landslides and gully erosion mobilise bedrock as well as POC, runoff erosion via overland flow removes only the surface layer of soil (Horton, 1945). If such processes are significant, the harvest of non-fossil POC stored in plants and soils could happen anywhere that there is enough rain on vegetated hillslopes to generate overland flow or shallow landslides.

Evidence for terrestrial POC export in temperate settings unaffected by rapid uplift and tropical storms exists in marine sediments

Abbreviations: POC, particulate organic carbon; tPOC, total particulate organic carbon; fPOC, fossil particulate organic carbon; nfPOC, non-fossil particulate organic carbon; C_{org}, organic carbon concentration; SS, suspended sediment; SSC, suspended sediment concentration; TSL, total suspended load; F_{nf}, modelled fraction of non-fossil organic carbon; F_{mod}, fraction of non-fossil organic carbon obtained from radiocarbon measurements; Q_e, effective discharge

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(Gordon and Goñi, 2003; Prahl et al., 1994) and in inputs to the ocean (Hatten et al., 2012), but there is still insufficient understanding of the processes which mobilise POC in the headwater source areas of these deposits. Here, we investigate POC sources and initial pathways under changing hydrologic conditions in a temperate, partly forested headwater catchment in the Swiss Prealps, where the runoff effect is not normally masked by deep-seated landsliding. We find strong evidence for runoff-driven transfer of significant amounts of modern soil-derived biomass during moderate hydrologic conditions, with the proportion of modern carbon in the suspended load increasing with discharge.

2. Study site

The Erlenbach is a first order tributary of the Alp River, located 40 km south of Zurich near the town of Einsiedeln. It has a small catchment area (0.74 km^2), elevation 1110–1655 m above sea level and average slope of 20% (Hagedorn et al., 2000). The mean annual air temperature is 6 °C and mean annual precipitation is 2300 mm (Hagedorn et al., 2001), 800 mm of this falling as snow in winter (Schleppi et al., 2004). The largest precipitation events occur as convective rainfall during the summer. In common with other small mountain river systems (Wheatcroft et al., 2010), discharge rises quickly during storms and is highly episodic in response to rainfall (Schleppi et al., 2006).

The catchment is developed on pelitic turbidites of the Eocene Wägital-Flysch Formation (Winkler et al., 1985). Recent glacial till overlies these rocks, particularly at lower elevations with a cover of up to several metres thick on the lower left bank. Both bedrock and drift are fine-grained, clay-rich and impermeable, resulting in water-saturated gleysols. Creep landslides are common, particularly in the lower reaches where steep channel sides cut into active complexes developed mainly in the till. These incrementally deliver substantial amounts of sediment to the stream channel during winter, which is removed by summer storms (Schuerch et al., 2006). The Erlenbach lacks a well-developed riparian zone and has a step-pool morphology with both logs and boulders forming the steps (Turowski et al., 2009). The catchment is 40% forest and 60% wetland and alpine meadow (Turowski et al., 2009). The main tree species are Norway Spruce (*Picea abies*) and European Silver Fir (*Abies alba*), with some Green Alder (*Alnus viridis*) (Schleppi et al., 1999).

The Erlenbach is an experimental catchment of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) (Hegg et al., 2006). Over the time period 1983–2011 inclusive, discharge (Q) recorded at 10-minute intervals ranged from 0 to 11,950 l s^{-1} with an average (Q_{mean}) of 38.6 l s^{-1}. In this study, we report discharges relative to this value (as Q/Q_{mean}), as well as absolute values, to allow comparison to other catchments. Over the monitoring period, flow was less than or equal to Q_{mean} for 77% of the time, with such discharges accounting for about 1% of suspended sediment transport. Less than 1% of discharges were above the threshold at which substantial bedload transport starts, which corresponds to Q/Q_{mean} ~13 (Turowski et al., 2011). The catchment is also a site for the NITREX project (NITRogen saturation EXperiments) (Wright and Rasmussen, 1998), and has three <1 ha sub-plots equipped with V-notch weirs in forest, forest with experimental nitrogen addition, and meadow (Schleppi et al., 1998).

3. Methods

POC in riverine suspended sediment is a mixture of carbon from two or more end member sources (Blair et al., 2003; Hilton et al., 2008a, 2008b; Komada et al., 2004; Leithold et al., 2006). It is particularly important to distinguish between carbon from fossil and non-fossil sources, because re-burial of fossil carbon has no effect on contemporary CO_2 drawdown, while burial of non-fossil carbon bypasses the usual rapid oxidation pathway and sequesters carbon (Berner, 1982). Mixing relationships can be primarily elucidated in N/C-δ^{13}C and C/N-δ^{15}N space (e.g. Hilton et al., 2010), while ^{14}C provides an additional constraint on the input of fossil carbon (e.g. Blair et al., 2003; Hilton et al., 2008b; Komada et al., 2005).

3.1. Sample collection

Instantaneous suspended sediment samples were collected direct from the stream at the upper gauging station in 100 ml plastic bottles, every few minutes during five storm events in July 2010. The largest of these (12 July) had a return period of about one year and a peak discharge of 2290 l s^{-1}, corresponding to a Q/Q_{mean} of ~59. The remaining four events took place within 10 days and covered a range of peak discharges from 300 to 1580 l s^{-1} (Table 1). With the exception of the 12 July event, the storms were characterised by intermittent rain. The hydrographs for three of the events are shown in Fig. 1. After collection, each turbid sample was passed through a 0.2 μm nylon filter within two weeks (mostly within three days), following interim storage at 5 °C. The filters with sediment were stored in glass petri dishes at −18 °C before lyophilization.

110 samples from potential sources for the riverine suspended sediment, including bedrock, surface soil, deeper soil profiles, foliage, wood, bedload and material from landslides and banks adjoining the channel, were collected between October 2009 and August 2010. All samples were stored in sealed plastic bags and oven-dried in covered foil dishes at <80 °C as soon as possible (1–12 days) after collection.

Surface soil and foliage were collected in transects across the catchment at a range of elevations, covering all major geomorphologic and ecologic conditions. At each locality, samples as representative as possible of the immediate surroundings were taken. Surface soil (a combination of O and A layers) was collected from the top ~10 cm with a clean trowel, after removal of overlying vegetation. Although the timing of collection could potentially affect the isotopic composition of soil samples because more decomposed litter could be enriched in ^{13}C and ^{15}N (e.g. Dijkstra et al., 2008), the collection method and subsequent processing result in samples homogenised over a long enough period to negate any seasonal differences. Foliage included multiple samples, comprising needles, leaves and twigs from all sides, of the three main tree types and representative understory. Samples of woody debris embedded in landslides and the channel bed were also collected across the catchment. Throughout this study, 'foliage' and 'wood' are used as convenient terms for different types of standing biomass, and include all associated microbial organisms.

Table 1
Characteristics of the five storm events sampled.

Date	Approx. time (UTC+2)	Number of samples[a]	Peak Q (l s^{-1})	Peak Q/Q_{mean}[b]
12 July 2010	19.00–20.30	37	2290	59
22–23 July 2010	20.30–02.30	37+1 preceding	420	11
26 July 2010	21.00–00.00	16+1 preceding	300	8
29 July 2010	06.30–16.45	25	1190	31
30 July 2010	08.45–16.00	9	1580	41

[a] Additional samples for 22 and 26 July were collected at intervening low flow.
[b] Q/Q_{mean} is the discharge relative to the average discharge over the period 1983–2011 inclusive (38.6 l s^{-1}).