Organic carbon concentrations in hyporheic zone sediments: A tool for measuring stream integrity

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Abstract

Effects of channel incision on sand-bed stream carbon reservoirs were examined. Channel incision may deplete hyporheic zone C stores due to bed erosion, less frequent hydrologic exchanges between stream and floodplain, and paucity of riparian vegetation and large woody debris. Presented are organic C concentrations found in hyporheic sediments before and after an incised stream rehabilitation project and in three adjacent streams in northern Mississippi. The sampled streams comprise a spectrum of physical conditions corresponding to the conceptual channel evolution model (CEM). Carbon concentrations in the upper 10 cm of the bed ranged from 0.24 $\pm$ 0.36% for a nonincised reference site to only 0.01 $\pm$ 0.02% for aggradational incised channels. Carbon concentrations generally declined with increase in stage of the CEM, increased with increasing percent canopy over the study reach and were not directly related to large woody debris (LWD) density. These findings suggest factors linking ecological degradation to channel incision and prospective pathways for stream rehabilitation design.

Introduction

Allochthonous input of various forms of organic matter into stream ecosystems forms the basis of the detrital food web (Minshall 1967, Fisher and Likens 1973, Vannote et al. 1980). Lower order streams often receive the majority of allochthonous organic matter from terrestrial leaf litter, large woody debris and soil particles that are washed into the stream from the watershed (Allan 1995). Particulate organic matter (POM) is a vital component of stream energy budgets (Cummins 1974) and influences consumer populations (Webster 1983). POM concentrations in hyporheic zones (Runkel et al. 2003) reflect a balance among inputs, transport, and retention (Wallace et al. 1982). POM retention has been linked to the local hydraulic regime, density of riparian vegetation, and presence of instream retentive structures (e.g., LWD) (Allan 1995). Human activities that perturb streams often reduce the concentrations of POM in sediments. Documented cases include studies of flow augmentation (Hauer 1989) and LWD removal (Bilby and Likens 1980). Although the detrimental effects of channel incision on stream habitat quality, particularly in warmwater sand-bed streams, have been described (Shields et al. 1994), the impacts on bed C reservoirs have not. Channel incision may deplete hyporheic zone C stores due to bed erosion, less frequent hydrologic exchanges between stream and floodplain, and paucity of riparian vegetation and LWD (Fig. 1). This study tests the hypothesis that organic C concentrations in sediments of small sand-bed streams are governed by the same geomorphic and hydraulic variables that control channel stability and physical habitat quality.

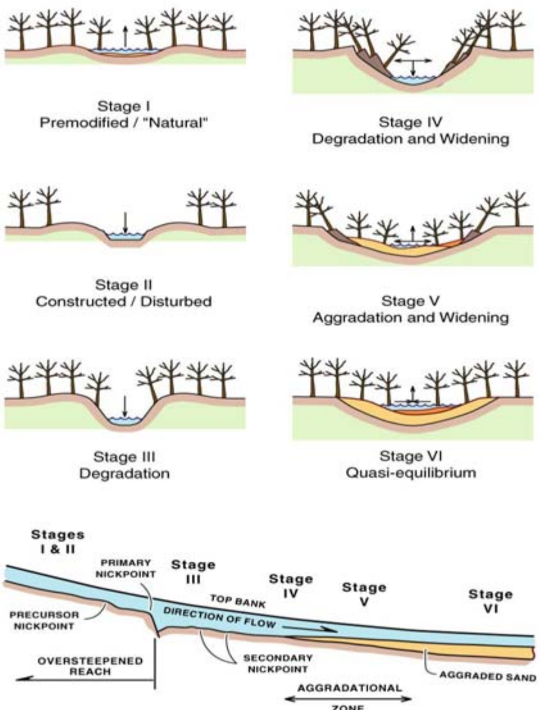

Fig. 1. Stages of channel incision corresponding to the channel evolution model (CEM) by Simon (1989)

Study sites

This study focuses on four sand-bed streams in north central Mississippi with varying degrees of habitat degradation: Hotophia Creek (HC), Toby Tubby Creek (TTC), Little Topashaw Creek (LTC) and Turkey Creek (TC) (Fig. 2). Watershed characteristics for these sites are summarized in Table 1. Streams in this region (humid southeast) are characterized by pulses of water and organic matter input that occur throughout the year. Nonincised channels are dominated by LWD and frequent exchange materials with adjacent floodplains and wetlands. European settlement in this area, which began in the 1830's, was followed by deforestation, cultivation, rapid erosion of hillsides, and accelerated valley sedimentation (Happ et al. 1940). Between 1840 and 1930 landowners and drainage districts attempted to improve utility of valley bottoms by channelizing the streams. Channelization by federal agencies also occurred between 1930 and

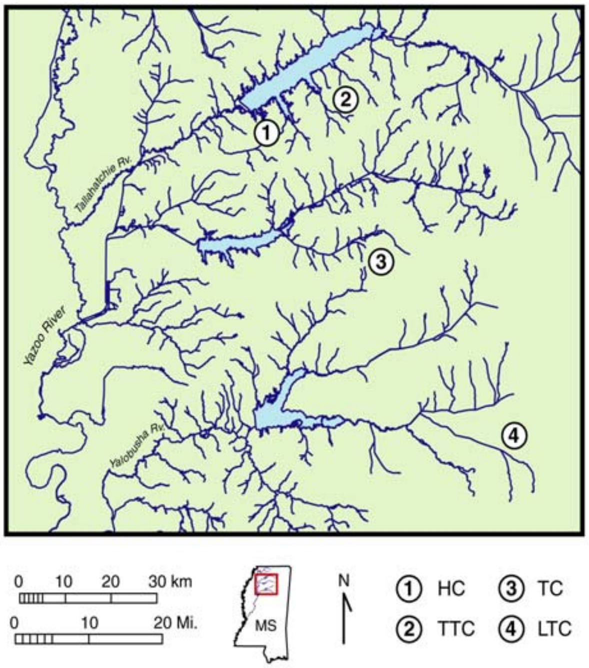

Fig. 2. Location of study sites

1945. These activities led to channel incision and loss of riparian vegetation. Characteristics of each study reach are summarized in Table 2. LTC and HC are fourth and fifth order, highly degraded streams with high levels of channel incision as described along a gradient corresponding to the channel evolution model (Fig. 1, Simon 1989). Both LTC and HC have bed material comprised of medium sand with slopes of 0.002 and 0.001, respectively. Outcrops of consolidated, cohesive material and derivative gravel-sized particles occurred along LTC (Adams 2000).

Table 1. Characteristics of Study Site Watersheds

Stream	Area (km^2)	% Forest or Water	% Row Crops	% Idle or Pasture
LTC	37	77	11	12
TC	46	86	0	14
TTC	38	69	31	0
HC	91	52	8	40

A stream restoration project was constructed along LTC in 2000, shortly after it was sampled. Restoration involved construction of 72 LWD structures using 1200 felled trees and planting 4000 willow cuttings on sandbars (Shields et al., 2001). TC and TTC are lightly degraded reference streams with plentiful riparian vegetation and LWD (Table 2). TC and TTC had bed composed of medium sands with slopes of 0.001 and 0.002, respectively.

Table 2. Physical Characteristics of Study Sites

Stream	CEM Stage	Canopy (%)	Mean LWD Density (m^2/km^2)	Thalweg Sinuosity	D_{50} (mm)	Additional information
2000 LTC	IV & V	25	46,500	2.1	0.28	Shields et al. 2001
2003 LTC	IV & V	27	111,800	2.2	0.29	Shields et al. 2001
TC	early III	65	113,100	1.3	0.45	
TTC	I	62	41,900	1.3	0.40	Shields et al. 1994
HC	IV	4	1,500	1.4	0.40	Shields et al. 1994, 1995

Methods

Samples of the top 10 cm of hyporheic zone sediments, including organic matter lying on the bed surface, were taken from channel transects during base flow. At each transect, ~250 g samples were taken from the channel centerline and from the region between edge and the quarterpoint of the base flow channel. Visual descriptions of the samples and stream characteristics were recorded at each transect. Samples were collected in summer of 2000 at LTC, prior to rehabilitation, and three years later. Samples were collected from the same 39 transects that were spaced at fairly uniform intervals along the 2 km study reach. In 2003, 9 transects upstream and 18 transects downstream of this reach were also sampled. The upstream sample sites were selected to characterize the contributing watershed, while the downstream sites were located along a channelized reach influenced by backwater conditions due to a major sediment and debris plug (Simon and Thomas 2002). Similarly, samples were also collected in the summer of 2003 at TC from 39 transects along the 1.5 km study reach and at selected transects upstream and downstream. Samples were collected from TTC and HC in December 1991 and January 1992, respectively. Thirty-six samples were collected from three evenly-spaced transects within each of four, 100-m sampling zones distributed along a 1-km reach.

All samples were analyzed for total C. We assumed that the contribution of inorganic C to total C was negligible due to the low pH regime typical of sediments and waters throughout this region, and therefore, total carbon = total organic carbon. This approach was verified by analyzing a subset of samples for TOC. Samples were dried, ground, forced through a 2 mm sieve, homogenized and subsampled to a weight of 0.5 - 1.0 g. Subsamples were analyzed for total C via dry combustion using a LECO CN2000 at a temperature of 1300 – 1350 ^{o}C (LECO CR12 at a temperature of 1400 ^{o}C for TTC and HC). Calibration was performed by using LECO soil standards and calibration checked with EDTA, Synthetic C and NAPT exchange soil samples.

Data were analyzed using summary statistics, graphical techniques, and analyses of variance. Due to their non-normal distribution, carbon concentrations were transformed by arcsine $(\%C \div 100)^{1/2}$ prior to statistical analysis (Sokal, 1981). To facilitate comparison of C concentrations with controlling variables, data were grouped by subreaches that were 100 to 150 m long. Based on field notes, categorical values for LWD density, canopy, and CEM stage were assigned to each subreach. Debris density and canopy levels were classified as high (debris - >80000 m^2/km^2; canopy - > 60%) or low (debris - < 80000 m^2/km^2; canopy - < 60%).

Results

Carbon concentrations and their variability were an order of magnitude higher for the lightly degraded reference sites (TT and TTC) than for the most degraded, incised stream (HC) (Table 3, Fig. 2). Isolated, relatively high (>0.5%) concentrations of C were associated with samples crumbled from consolidated cohesive scarps and outcrops in the upstream portions of LTC (Fig. 3). Since this C was not associated with POM, these values were excluded from statistical analyses. Even so, distributions of hyporheic C in HC and TC were not normal (K-S test, $p < 0.05$) even following arcsine transformation (Table 3). Carbon concentrations were intermediate for the rehabilitated stream (LTC), and mean concentrations were essentially unchanged three years after installation of LWD structures and willow planting. One-way ANOVA based on ranks indicated that C concentrations for the highly degraded HC were significantly lower, but differences among the other sites were not significant ($p < 0.05$).

Table 3. Total Carbon Concentrations for Selected Reaches of Sand-Bed Streams in North Central Mississippi

Stream	Mean ± Std Dev (%)	Skewness	Transformed Skewness	Kurtosis	Transformed Kurtosis
HC	0.01 ± 0.02	1.15	1.13	0.57	0.46
2000 LTC	0.13 ± 0.08	1.18	1.03	0.82	0.42
2003 LTC	0.14 ± 0.15	5.56	3.79	42.55	22.74
TC	0.24 ± 0.33	2.34	1.83	5.78	2.82
TTC	0.26 ± 0.36	3.23	2.17	13.01	5.79

The lightly degraded streams (TTC, TC), which had more abundant LWD, more canopy, and more stable boundaries, exhibited higher C concentrations in their beds (Fig. 3). Although ANOVA indicated that C declined with advances in channel evolution ($p = 0.015$, $F = 3.55$) and increased with increasing riparian canopy ($p < 0.001$, $F = 11.06$), differences based on LWD density were not significant ($p < 0.9$, $F = 0.156$, Fig. 4). Two-way ANOVA using stream and lateral position (channel centerline versus channel sides) as factors showed that C concentrations were significantly higher along channel margins within lightly degraded streams, but not in actively incising streams (Fig. 5). Average (± std.dev.) C concentration along the centerline in TTC was 0.11 ± 0.14% versus 0.31 ± 0.41% along the channel margins. Average centerline concentration in TC was 0.14 ± 0.13% versus 0.32 ± 0.39% along the margins.

Hyporheic sediment C concentrations increased in the receiving stream downstream from the LTC study reach in 2003 (Fig. 6). Bed C concentrations averaged 0.43 ± 0.37% in aggrading stage V reaches downstream (Simon and Thomas, 2002) compared to 0.14 ± 0.15% within the study reach and in stage III reaches of low order tributaries upstream. This difference was not significant ($p = 0.065$). Carbon concentrations were more uniform in the less-disturbed TC watershed, but the downstream mean represents only three samples from one transect (Fig. 6).

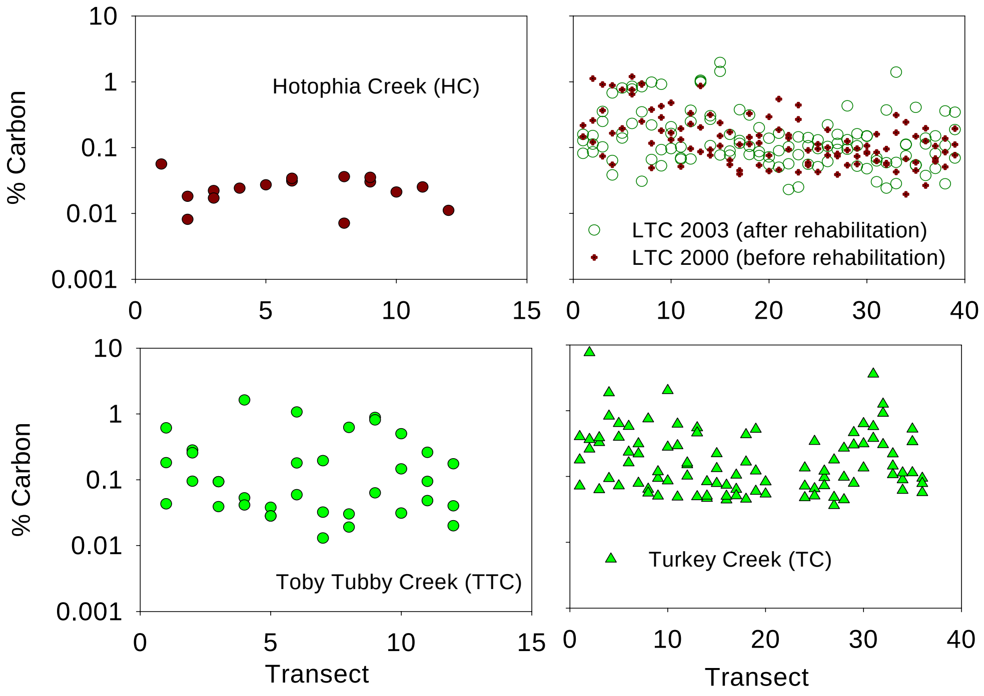

Fig. 3. Hyporheic sediment total C concentration for selected reaches of four streams in northwestern Mississippi. Logarithmic scale on vertical axis.

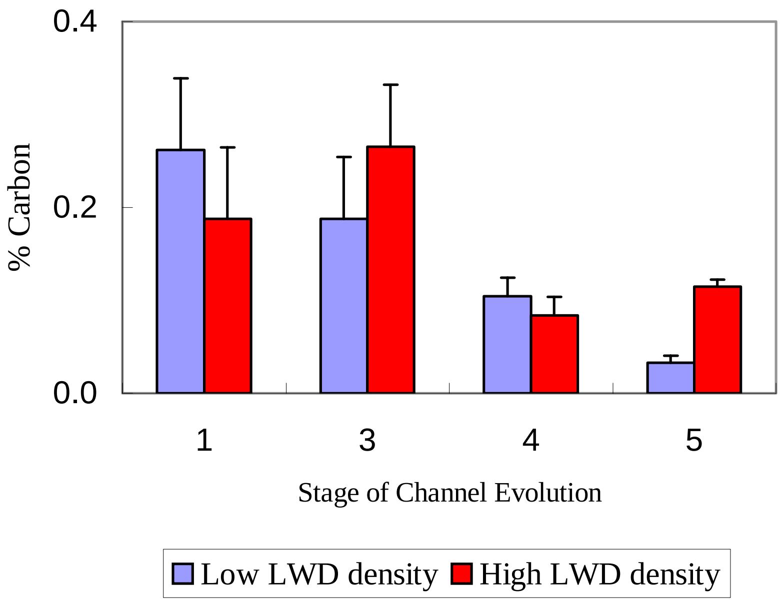

Fig. 4. Hyporheic sediment total C concentrations as a function of LWD density and stage of channel evolution for selected reaches of four streams in northwestern Mississippi. Vertical bars represent standard error.

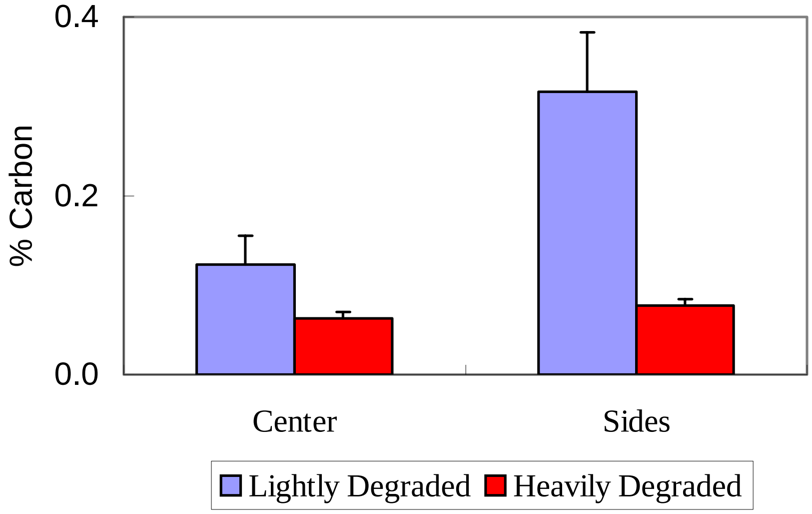

Fig. 5. Hyporheic sediment total C concentrations along baseflow channel centerlines and margins for selected reaches of two lightly degraded and two incising streams in northwestern Mississippi. Vertical bars represent standard error.

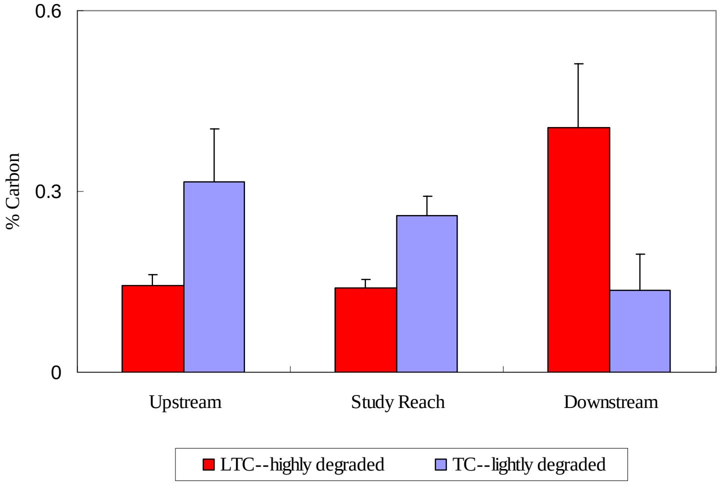

Fig. 6. Hyporheic sediment total C concentrations within study reaches and in upstream and downstream channels within larger watersheds of streams in northwestern Mississippi. Vertical bars represent standard error.

Discussion

Organic material on streambeds and within hyporheic zones has been studied extensively, but the range of methods for measuring C concentrations and expressing results makes comparison difficult. The concentrations of total C (assumed equal to TOC) observed in these streams ranged from near detection limits (0.01%) to 13%, and were generally lower than reported for other systems. Hauer (1989) examined two blackwater streams in South Carolina where one stream had been subjected to prolonged flow augmentation and thermal discharge and was lacking riparian vegetation and LWD, while the other was a reference site with plentiful riparian vegetation and dense canopy. TOC in sediments of the disturbed stream were less than 1% while the reference stream was over 30%. Rostan et al. (1987) reported organic C concentrations in permanently inundated abandoned river channels along the Upper Rhone in France ranging from 0.37 to 23.1%

We found concentrations of C in the hyporheic zone of sand-bed streams were controlled by the same variables that control channel stability and physical habitat quality. In our study, C concentrations were found to proportionally reflect the density of riparian canopy and extent of channel erosion by incision-related processes. C concentrations were not reflective of LWD density, in contrast to earlier work by others (Bilby and Likens 1980; Hauer 1989). In this study, nonincised reaches having the highest concentrations of hyporheic C did not have consistently high debris densities. Conversely, incision processes in some reaches evidently had triggered accelerated LWD inputs in the form of undermined trees (Downs and Simon 2001). Furthermore, the efficiency of LWD formations as POM retention devices is not fully reflected in simple debris density, since debris lying parallel to the flow direction along the channel margins does not retain POM as well as debris dams that slow water velocities and permit the deposition of fine material. The addition of debris structures at LTC was not followed by an increase in bed C concentrations, despite the fact that these structures reduced mean flow velocities during 2001 (Shields et al. 2003). Our results likely reflect the fact that nearly 70% of the structures had been severely damaged or destroyed by 2003 (Shields et al. 2004). The structures were applied to channel margins in order to address processes associated with high flows; slight amounts of scour were actually observed along the channel centerline. Analysis of sediment grain sizes in the channel and on adjacent bars and banks in 1999 prior to debris structure addition and in 2003 showed little change in the channel itself, but did show a significant fining trend along sides of the channel (Unpublished data, National Sedimentation Laboratory). These findings are consistent with higher concentrations of total C along channel margins shown in Fig. 5.

In general, high levels of stream biological diversity are associated with natural patterns of physical heterogeneity and high levels of physical diversity (Gorman and Karr 1978). The variance within the data collected can also be a good indicator of stream integrity. The lightly degraded streams in this study had significantly higher variation in hyporheic C than streams impacted by accelerated erosion, reflecting the higher velocities, flashier hydrology, frequent bed movement, and lack of riparian vegetation and debris typical of incising streams (Shields et al. 1994). Variations along the lightly degraded streams displayed both random and systematic components, with significantly higher concentrations of C along channel margins relative to the centerline.

In general, hyporheic C concentrations were lower in the reaches disturbed by channel incision with the exception of transects sampled in the receiving stream downstream from the LTC study reach. This stretch was dominated by a major downstream sediment and debris plug (Simon and Thomas 2002) which yielded lower water velocities and major deposition of organic matter and inorganic sediments. Bed sediment C was positively associated with riparian canopy, as noted by Hauer (1989). In watersheds disturbed by incision, canopy is related to channel evolution since widening that occurs as incision progresses destroys riparian buffers and produces wider channels that require taller vegetation for canopy cover (Fig. 1).

Conclusions

Total C concentrations in the hyporheic zones of sand-bed channels subject to incision, headwater erosion, and downstream deposition, varied from 0.01% in a highly degraded reach with little riparian vegetation, to about 0.4% in an aggradational reach blocked by a major sediment debris plug. In general, lightly degraded reaches had higher concentrations of C, and wider variation than those actively eroding. Debris density was a poor predictor of C retention, probably due to the inability of debris density values to adequately reflect C retention processes, and because elevated debris densities are often associated with the initial stages of channel incision.

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