



# Benthic control on the statistical distribution of transported sediment carbon in a low-gradient stream

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## SUMMARY

Results from a numerical model that simulates particulate organic carbon source, fate and transport were used to generate the statistical distribution of transported sediment carbon in a low-gradient, agriculturally-impacted stream over a five-year model simulation. Results suggest that the statistical distribution of transported sediment carbon is Gamma distributed (RMSEA = 0.066) for the low-gradient stream. The distributional form of transported sediment carbon is governed by seasonal variability of temporarily stored benthic carbon and the relative contributions of benthic, bank and upland carbon sources. Results of the study suggest that shape and skew of the Gamma distribution are governed by biological activity (i.e., autochthonous production and decomposition) of the streambed. Analysis was performed to examine how field sampling factors, including flow conditions during sampling, sampling frequency, and the sampling temporal domain including event, seasonal and annual variability, capture the statistical distribution of transported sediment carbon. Contrary to conventional wisdom, sampling flow conditions and sampling frequency showed little impact on the sampled distribution of transported sediment carbon, which reflects the amalgamation of streambank and upland carbon sources on the stream bed in this low-gradient stream. Annual variability, i.e., wet and dry years, and seasonal variability were needed to adequately capture the statistical distribution of transported sediment carbon, which reflects the stochastic nature of the hydrologic regime annually and the seasonal variability of biological processes. The results provide a testable hypothesis, and a sampling design approach, for the statistical distribution of transported sediment carbon in low-gradient systems where benthic biological processes are prominent.

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## 1. Introduction

Organic carbon associated with fine sediment particles and sediment aggregates is now recognized to promote benthic carbon cycling at local stream scales, fuel heterotrophic bacteria that can transform and remove nutrients from the streamwater, and have significant implications for carbon budgeting at regional and global scales (Arango et al., 2007; Cole et al., 2007; Arango and Tank, 2008; Battin et al., 2009; Alvarez-Cobelas et al., 2010; Tank et al., 2010; Akamatsu et al., 2011; Findlay et al., 2011; Newcomer et al., 2012; Ford and Fox, 2014). However, recent literature suggests that reliable estimates of sediment carbon in streams is lacking, and a number of studies point to the need for transported sediment carbon ( $\text{gC } 100\text{gSed}^{-1}$ ) data to help reduce uncertainty

in carbon budget assessments and to predict the composition of benthic carbon in downstream river reaches (Dalzell et al., 2005; Cole et al., 2007; Battin et al., 2009; Alvarez-Cobelas et al., 2010; Akamatsu et al., 2011). Of particular recent interest are streams that are low-gradient and agriculturally-impacted in which riparian canopy removal and high nutrient inputs from fertilizers promote benthic autotrophic production, and low stream and hillslope gradients promote pronounced benthic sediment storage (Walling et al., 2006; Battin et al., 2009; Russo and Fox, 2012; Ford and Fox, 2014). Low-gradient, agriculturally-impacted streams are now recognized to play a dominant role in freshwater carbon cycling and associated downstream water quality due to the net large land masses they cover and their high nutrient loads that promote in-stream carbon cycling (Alexander et al., 2008; Mulholland et al., 2008; Griffiths et al., 2012). In this paper, we focus on analyzing transported sediment carbon, symbolized here as  $C_T$ , over a five year time period in a low-gradient, agriculturally-impacted stream. Specifically, we examine the statistical distribution of  $C_T$  exported from the watershed over the five-year period and investigate the

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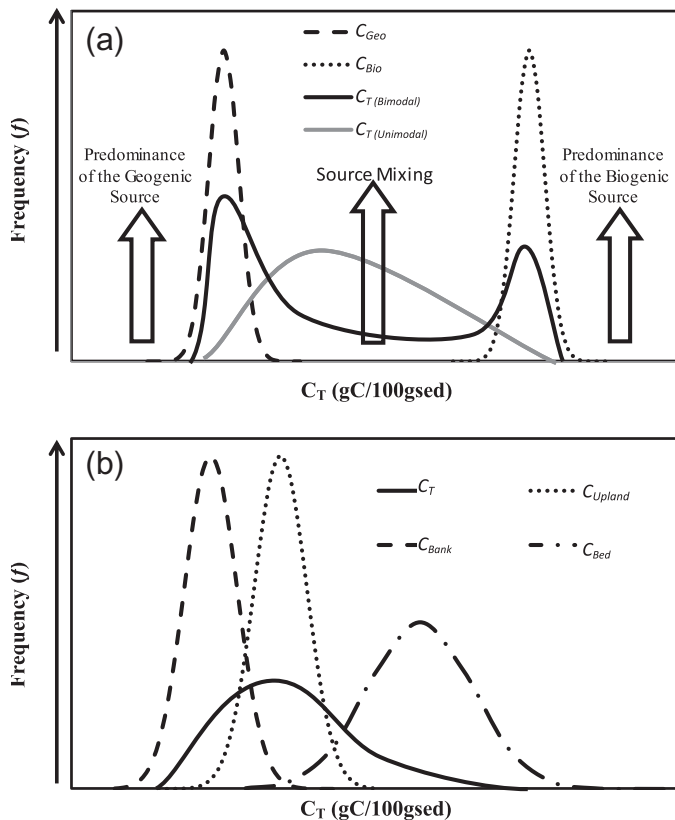
importance of field sampling design factors on representing the statistical distribution of  $C_T$ .

While the statistical distributions of water (Nash, 1994; Segura et al., 2013) and sediment (Parker and Troutman, 1989; Benkhald et al., 2013) transported in streams have been heavily investigated historically in hydrology research, less emphasis has been placed on the statistical distribution of  $C_T$ . The body of knowledge surrounding the statistical distribution of  $C_T$  has tended to center around transported carbon quality in small, steep mountainous streams due to the fact that steep systems can export high carbon loads over relatively short distances (Masiello and Druffel, 2001). Research of steep streams over the past decade has tested the hypothesis that  $C_T$  follows a bimodal distribution in which sources of carbon enriched biogenic sediments, i.e., surface soils with relatively short residence times, are activated during low flows, sources of carbon depleted geogenic sediments, i.e., deep soils or bedrock, are mobilized during high flows, and in-stream sources are neglected as a result of low storage and autochthonous production (Masiello and Druffel, 2001; Lyons et al., 2002; Gomez et al., 2003; Coynel et al., 2005; Leithold et al., 2006; Hilton et al., 2008, 2012; Blair et al., 2010; Gomez et al., 2010). A definition sketch of  $C_T$  in small mountainous rivers is provided in Fig. 1a. Theoretically,  $C_T$  will be unimodal if either a single carbon source is reflected (e.g., biogenic source), heterogeneous source mixing occurs under different flow regimes, or if two carbon sources have similar carbon concentrations. A bimodal distribution is expected when different flow regimes preferentially erode and transport a unique source such as high flows erode and transport deep geogenic sources while low flows erode and transport surface soils. To our knowledge, no studies have examined the statistical distribution of  $C_T$  in low-gradient, agriculturally-impacted streams despite the fact that numerous studies have measured  $C_T$  data and calculated

statistical moments, i.e., mean, variance, skewness, and kurtosis, for low-gradient streams (Munson and Carey, 2004; Dalzell et al., 2005, 2007; Schuster et al., 2008; Oeurng et al., 2011; Owens and Shipitalo, 2011; Griffiths et al., 2012).

It is recognized that the statistical distribution of  $C_T$  in streams will reflect the carbon sources and their relative contributions to the fluvial carbon load. Further, the  $C_T$  distribution reflects both carbon quantity and carbon quality because carbon sources have different levels of bioavailability and organic matter compositions. For lowland systems, newly generated benthic carbon is a higher quality source than terrestrial carbon as a result of higher energy per unit mass and less recalcitrant carbon-compounds such as lignin and cellulose (Thorp and Delong, 2002; Lane et al., 2013). We hypothesize for low-gradient systems that a unimodal distribution will exist because algal biomass varies seasonally and will be integrated with bank and upland carbon in the streambed as suggested in Fig. 1b. The lowland system transports heterogeneous source contributions of upland, bank and benthic carbon in which the benthic source is an amalgamation of previously deposited and newly generated carbon (Ford and Fox, 2014). A unimodal  $C_T$  distribution is further promoted when carbon distributions of bank, upland and bed sources overlap. The transport of soil and streambank originated carbon and its imprint upon the  $C_T$  distribution in low-gradient streams is expected to be analogous to steep streams in that carbon rich surface sediments will be eroded from the uplands during moderate hydrologic events while depleted, lower quality carbon from deeper soils and streambank sources will be transported during high magnitude hydrologic events (Toy et al., 2002; Jacinthe et al., 2009; Kim et al., 2010). However, the impact of temporarily stored and generated streambed sediment carbon upon the statistical distribution of  $C_T$  is less predictable as streambed carbon is expected to show variability across numerous time scales (Cole et al., 2007; Battin et al., 2009; Griffiths et al., 2012; Ford and Fox, 2014). The make-up of streambed sediment carbon will reflect recent hydrologic events that deposit sediment to the streambed, heterotrophic bacterial decomposition and autotrophic production of organic carbon that varies seasonally in the streambed, and longer-term hydrologic variability that has been shown to impact streambed carbon annually (White et al., 1991; Rutherford et al., 2000; Ford and Fox, 2014). The complexity added to carbon transport in low-gradient, agriculturally-impacted streams via the streambed source and the instantaneous nature of  $C_T$  sampling suggests the need for estimating the statistical distribution of  $C_T$  using population estimates that encompass event, seasonal, and annual variability.

Due to the fact that the statistical distribution of  $C_T$  has not been examined in low-gradient agriculturally-impacted streams, questions remain regarding an appropriate field sampling routine to estimate the statistical moments of  $C_T$  (e.g., statistical mean, variance, skewness, and kurtosis). Review of past literature suggests that few studies have specifically focused on measuring  $C_T$ , however numerous studies measure  $C_T$  to support broader environmental studies, e.g. particulate organic carbon (POC) flux estimates under varying flow conditions, and foodweb studies. Sampling protocol for  $C_T$  varies widely; however factors including flow conditions, temporal domain and sampling frequency are considered important in most studies. With regard to flow conditions, recent studies have placed a heavy emphasis on  $C_T$  during high flows (Masiello and Druffel 2001; Worall et al., 2003; Dalzell et al., 2005, 2007; Oeurng et al., 2011; Owens and Shipitalo, 2011) with only a few studies assessing the importance of  $C_T$  at low flows (e.g. Griffiths et al., 2012). The temporal domain also has been varied with multi-year and single-year datasets used equally to estimate  $C_T$  (Cuffney and Wallace, 1988; Lyons et al., 2002; Gomez et al., 2003; Worall et al., 2003; Sharma and Rai, 2004; Leithold et al., 2006; Aldrian et al., 2008; Zhang et al.,



**Fig. 1.** Definition sketch for a hypothetical  $C_T$  probability density function in (a) small mountainous rivers and (b) low-gradient, biologically active agricultural streambeds.

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