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Research papers

Impact of landscape disturbance on the quality of terrestrial sediment carbon in temperate streams

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ABSTRACT

Recent studies have shown the super saturation of fluvial networks with respect to carbon dioxide, and the concept that the high carbon dioxide is at least partially the result of turnover of sediment organic carbon that ranges in age from years to millennia. Currently, there is a need for more highly resolved studies at stream and river scales that enable estimates of terrestrial carbon turnover within fluvial networks. Our objective was to develop a new isotope-based metric to estimate the quality of sediment organic carbon delivered to temperate streams and to use the new metric to estimate carbon quality across landscape disturbance gradients. Carbon quality is defined to be consistent with in-stream turnover and our metric is used to measure the labile or recalcitrant nature of the terrestrial-derived carbon within streams. Our hypothesis was that intensively-disturbed landscapes would tend to produce low quality carbon because deep, recalcitrant soil carbon would be eroded and transported to the fluvial system while moderately disturbed or undisturbed landscapes would tend to produce higher quality carbon from well-developed surface soils and litter. The hypothesis was tested by applying the new carbon quality metric to 15 temperate streams with a wide range of landscape disturbance levels. We find that our hypothesis premised on an indirect relationship between the extent of landscape disturbance and the quality of sediment carbon in streams holds true for moderate and high disturbances but not for undisturbed forests. We explain the results based on the connectivity, or dis-connectivity, between terrestrial carbon sources and pathways for sediment transport. While pathways are typically un-limited for disturbed landscapes, the un-disturbed forests have dis-connectivity between labile carbon of the forest floor and the stream corridor. Only in the case when trees fell into the stream corridor due to severe ice storms did the quality of sediment carbon increase in the streams. We argue that as scientists continue to estimate the in-stream turnover of terrestrially-derived carbon in fluvial carbon budgets, the assumption of pathway connectivity between carbon sources to the stream should be justified.

1. Introduction

Carbon cycling in streams and rivers has garnered much recent interest in the scientific community due to is potential impact on regional and global carbon cycles and control of freshwater ecosystems (Butman and Raymond, 2011). Carbon enters the fluvial system from landscapes through water runoff, subsurface water recharge and lateral flow, landslides and mass wasting, and direct deposits such as leave fall. Input carbon pools take the forms of dissolved inorganic and organic carbon, plant material and coarse particulate organic carbon, fossil-like sediment carbon from weathered bedrock and deep soils, and terrestrially-derived (non-fossil) sediment organic carbon. Within the fluvial system, it is now recognized that microbial communities are rather efficient in their oxidation of dissolved and active particulate carbon pools resulting in carbon dioxide bi-product and increasingly degraded terrestrially-derived carbon longitudinally in a fluvial system (Battin et al., 2009). In the meantime, autotrophic biota including algae and macrophytes add a newly generated carbon pool to the in-stream load while being fairly labile to turnover in the presence of the instream microbial community (Ford and Fox, 2014; Hotchkiss and Hall, 2015). The net result is a fluvial system which behaves to transport but also actively oxidize carbon and results in carbon dioxide super saturation of rivers, degassing of carbon dioxide to the atmosphere, and export of dissolved and particulate

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carbon pools to lakes and estuaries (Butman and Raymond, 2011; Regnier et al., 2013).

One of the most highly uncertain carbon pools within the fluival carbon cycle is the terrestrially-derived sediment organic carbon. Terrestrially-derived sediment organic carbon exists as an intermediate stage carbon pool for which open questions remain regarding its turnover and temporary burial and removal from active carbon cycles (Cole et al., 2007). Agreement exists that terrestrially-derived sediment organic carbon, which is transported from soil systems and to streams, reflects its plant origin and may be decomposed to some more recalcitrant state (Marin-Spiotta et al., 2014). However, spatial variability of the decomposition state and thus in-stream quality of sediment organic carbon across fluvial systems and within fluvial systems is not well understood. Recent results suggest wide variability across fluvial systems possibly reflecting highly labile carbon that is close in composition to its plant origin with a turnover time of just a few years to highly recalcitrant sediment carbon with a turnover time on the order of thousands of years (Marwick et al., 2015). The motivation of this paper is to improve understanding of the quality of sediment organic carbon transported from different landscapes to the fluvial environment.

Study of sediment organic carbon quality in streams relies on consideration of source processes in soil systems to produce labile or recalcitrant carbon and pathways for transport of sediment carbon from landscapes to the fluvial environment. Source processes to produce carbon quality of various stages rely on integration of plant-derived organic matter to soils. In general, soils are characterized by the inputs of litter carbon and root carbon that are gradually decomposed and physically mixed down the soil column producing more highly decomposed, low quality carbon deeper in soil and newer, more labile carbon near the soil surface (Nadelhoffer and Fry, 1988; Acton et al., 2013). In turn, the vertical distribution of soil carbon quality is coupled with particle and aggregate erosion-related source processes. For example, surface dominated interrill and shallow rill erosion processes erode high quality surface carbon while deep rill and gully erosion, subsurface piping erosion, and bank incision tend to erode low quality subsurface carbon. Finally, the net loading of the quality of sediment carbon to streams relies on the connectivity of source processes to pathways for transport. Overland (surface) flow pathways, macropore (subsurface) flow pathways, and more direct, immediate pathways associated with fluvial transport and mass wasting of bank sediments in the stream corridor all have the potential to provide connectivity between terrestrial carbon quality at surface and subsurface sources and streams.

As we move towards estimation of the spatial variability of upland-produced sediment carbon quality in streams, we must consider how different landscape disturbances might impact both source processes to produce different quality carbon stocks and the existence of, or lack thereof, pathways for transport. Our hypothesis with respect to the quality of terrestrially-derived sediment organic carbon transported in streams is that intensively-disturbed landscapes would tend to produce low quality sediment organic carbon while moderately disturbed or undisturbed landscapes would tend to produce higher quality carbon. For example, intensively-disturbed landscapes that expose poor quality carbon due to deep plowing or reworking of the landscape coupled with non-limited pathways from deep rills and gullies would be expected to produce low quality sediment carbon to the fluvial system. Best management practices that moderate the landscape disturbance, improve the soil carbon quality, and keep open the pathways for transport would be expected to show improved quality sediment carbon in streams. However, the expected results of carbon quality exported from many landscapes might not be so straightforward when the intersection of source processes and pathways for transport do not produce a net positive product. Connectivity or 'dis-connectivity' between source processes and pathways would be expected to impact the resulting sediment (Fryirs, 2013) as well as the transported sediment carbon quality. Compounding estimates of carbon quality is the fact that sediment carbon quality conveyed to streams can possibly show a divergence from traditional fluvial sediment transport studies that apportion sediment sources to streams (e.g., sediment fingerprinting studies, catchment erosion models) because carbon quality is often not commensurate with sediment transport rates (Marwick et al., 2015).

The objectives of this study were: (1) to develop a carbon quality metric based on the stable isotope composition of sediment carbon that varies in magnitude from zero, reflecting highly recalcitrant carbon, to one, reflecting highly labile carbon that is close in composition to its plant origin; and (2) to estimate the quality of terrestrially-derived sediment organic carbon transported to temperate streams with contrasting landscape disturbances. Isotope measurements of fluvial sediments and labile and recalcitrant end-members are used to estimate the carbon quality metric for 15 streams with their landscapes classified as low, moderate and highly disturbed. Thereafter, the authors discuss the results with respect to carbon sources processes and transport pathways.

2. Methods

2.1. Formulation of the carbon quality metric

We introduce a stable isotope-based metric, termed C_{qual} that quantifies the quality of terrestrially-derived sediment organic carbon in fluvial systems. The premise of the in-stream carbon quality metric is that the bioavailability of sediment carbon in fluvial system will be dependent on the molecular composition of the terrestrial derived sediments. Surface soils are typically high in carbohydrates and lignin with high C:N ratios, whereas deeper/processed soils have a significant contribution of microbial processed and synthesized compounds with smaller C:N ratios (Marin-Spiotta et al., 2014). The conceptual model of organic matter dynamics proposed by Marin-Spiotta et al., (2014) suggest less processed soils will have organic carbon concentrations that decrease at higher rates along the fluvial continuum as compared to microbially processed soils. In turn, highly bioavailable carbon within labile soil organic carbon will provide high energy production per unit mass of carbon as sediments in the fluvial system (Thorp and Delong, 2002; Ford et al., 2015a,b). Therefore, we find that using recalcitrance state of the terrestrial source as an indicator of in-stream sediment carbon quality is appropriate.

The biomarker chosen to estimate recalcitrance state for the present study is the stable carbon isotopic signature, $\delta^{13}C$, of sediment carbon. While biomarkers such as the radiogenic carbon isotope (^{14}C) has been found to be somewhat decoupled from the molecular structure of upland carbon, the stable isotopic signature $\delta^{13}C$ is inherently linked to the organic matter structure of carbon since it is insensitive to carbon age but sensitive to level of microbial processing (Acton et al., 2013). As microbes preferentially utilize the lighter ^{12}C isotope molecules within carbon bearing compounds for cell synthesis and respiration, more recalcitrant components are left enriched in ^{13}C (Sharp, 2007). This fractionation typically results in a deviation from its parent signature on the order of a few per mil allowing differentiation between the labile reactant and more recalcitrant product (Jacinthe et al., 2009; Dubois et al., 2010). Therefore, for a given parent material, the most ^{13}C enriched signatures, e.g., a recalcitrant carbon source, will have the lowest quality and the most ^{13}C depleted signatures,