Water Research 108 (2017) 432–443

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Stabilization of benthic algal biomass in a temperate stream draining agroecosystems

William I. Ford [a, *], James F. Fox [b]

[a] Division of Engineering, Marshall University, Huntington, WV, USA
[b] Civil Engineering Department, University of Kentucky, Lexington, KY, USA

ARTICLE INFO

Article history:
Received 25 March 2016
Received in revised form
25 October 2016
Accepted 6 November 2016
Available online 7 November 2016

Keywords:
Algal stabilization
Agroecosystems
Fluvial carbon budget
Watershed model

ABSTRACT

Results of the present study quantified carbon sequestration due to algal stabilization in low order streams, which has not been considered previously in carbon stream ecosystem studies. The authors used empirical mode decomposition of an 8-year carbon elemental and isotope dataset to quantify carbon accrual and fingerprint carbon derived from algal stabilization. The authors then applied a calibrated, process-based stream carbon model (*ISOFLOC*) that elicits further evidence of algal stabilization. Data and modeling results suggested that processes of shielding and burial during an extreme hydrologic event enhance algal stabilization. Given that previous studies assumed stream algae are turned over or sloughed downstream, the authors performed scenario simulations of the calibrated model in order to assess how changing environmental conditions might impact algae stabilization within the stream. Results from modeling scenarios showed an increase in algal stabilization as mean annual water temperature increases ranging from 0 to 0.04 tC km^{-2} $^{\circ}$C^{-1} for the study watershed. The dependence of algal stabilization on temperature highlighted the importance of accounting for benthic fate of carbon in streams under projected warming scenarios. This finding contradicts the evolving paradigm that net efflux of CO_2 from streams increases with increasing temperatures. Results also quantified sloughed algae that is transported and potentially stabilized downstream and showed that benthos-derived sloughed algae was on the same order of magnitude, and at times greater, than phytoplankton within downstream water bodies.

1. Introduction

Highly disturbed agroecosystem streams demand scientific investigation because they have broad spatial extent, hold significant weight within the freshwater carbon budget, and partially govern downstream carbon cycling (Butman and Raymond, 2011; Griffiths et al., 2012; Ford and Fox, 2014a). Agroecosystem streams often starkly contrast forested and steep gradient systems because they have open canopies that promote high light availability to streambeds for benthic algae production, upland agriculture that produces high nutrient inputs, and low stream gradients that facilitate benthic storage of organic matter and bacterial biofilms (Rutherford et al., 2000; Griffiths et al., 2012; Ford and Fox, 2014a). In turn, low-gradient agroecosystem streams harbor autochthonous carbon within bed sediments that can cause streambeds to have a high amount of stored carbon, a wide carbon pool distribution, and a highly variable stream carbon flux across events seasonally and annually (Dalzell et al., 2005; Griffiths et al., 2012; Ford and Fox, 2014a,b; Ford et al., 2015a; Fox et al., 2014). However, to our knowledge, no previous studies use long-term carbon datasets or numerical modeling to quantify C sequestration from algal stabilization in agroecosystem streams.

Algal stabilization is the coupled biotic-abiotic process by which algal biomass decomposes into more complex refractory carbon compounds in aquatic ecosystems for extended periods (Lara and Thomas, 1995; Leloup et al., 2013; Hotchkiss and Hall, 2015). At the watershed-scale, numerical models for fluvial carbon budgets broadly neglect contributions of algal stabilization to benthic carbon storage since the models treat benthic carbon as a 10 cm hydrodynamically static anaerobic layer (DiToro, 2001; Wool et al., 2006; Chapra et al., 2008; Park and Clough, 2012). In part, scientists support this assumption with the argument that algal biomass has a net zero effect on fixation and respiration in fluvial carbon

* Corresponding author. Division of Engineering, Marshall University, Huntington, WV, USA.
E-mail addresses: williamford@uky.edu (W.I. Ford), jffox@engr.uky.edu (J.F. Fox).

http://dx.doi.org/10.1016/j.watres.2016.11.026
0043-1354/

budgets due to its short turnover lengths and a tendency for algal carbon to fuel ecosystem services (Minshall et al., 1983; Griffiths et al., 2012; Hotchkiss and Hall, 2015). However, as stated previously, few, if any studies, use long-term C records to investigate this assumption.

The effect of long-term temperature shifts and extreme hydrologic events on algal stabilization and C sequestration is of particular interest given that flow regime and water temperature are two critical drivers of algal carbon dynamics in disturbed agroecosystems (e.g., Rutherford et al., 2000; Flynn et al., 2013). Flow regime has the potential to impact algal stabilization through episodic sloughing and downstream export of benthic periphyton, fluvial erosion of stabilized algae in the benthos, and burial of stabilized algae due to depositional fluxes (Droppo and Stone, 1994; Fovet et al., 2010; Graba et al., 2013; Flynn et al., 2013; Ford and Fox, 2014a). Since temperature is the primary biotic variable controlling algal production and the microbial decomposition of coarse and stabilized algal pools, agroecosystems often have non-rate-limiting nutrient and light conditions (Rutherford et al., 2000; Griffiths et al., 2012; Ford and Fox, 2014a). Recent studies suggest temperature gradient increases will promote decreases in net carbon sequestration by freshwater streams based on the argument that biotic respiration is more sensitive to temperature than autotrophic production (Yvon Durocher et al., 2011; Trimmer et al., 2012). However, these previous studies focused on short timescales and mesocosm-based experimentation due to the difficulties in obtaining long-term ambient datasets.

The objective of this study was to quantify C sequestration in agroecosystem streams as a result of algal stabilization. The authors apply an eight-year dataset of stream C elemental and isotope signatures to provide evidence of algae stabilization. Then, the authors apply a process-based stream C model to provide further evidence of algal stabilization and elucidate the physical and biological processes that govern algal stabilization. Next, the authors then use the process-based model to simulate how changing temperature and extreme hydrologic conditions provide external control on algae stabilization. Finally, the numerical simulations allow the authors to discuss existing paradigms of temperature variability on stream CO_2 efflux and the impacts of algal sloughing to downstream ecosystems.

2. Study system: agroecosystem stream

The 62-km^2 South Elkhorn watershed (Fig. 1) was chosen as a study site of algal stabilization because of the extensive knowledge of land use, flow, sediment and carbon dynamics in the system; the highly productive nature of the streambed; and the spatial and temporal variability of the dynamic benthos (Fox et al., 2010; Russo and Fox, 2012; Ford and Fox, 2014a,b; Fox et al., 2014; Ford et al., 2015a, 2015b; Ford and Fox, 2015). The South Elkhorn watershed is located in the Bluegrass Region of Central Kentucky and is a mixed-use watershed that is impacted by agricultural and urban land use. During the decade-long time period of water quality data collection, the agricultural land use (57%) was primarily horse farms, while urban land use (43%) was primarily residential and commercial. Storm flows drove precipitation, and subsequently streamflow and produced 1150 mm/year of precipitation and an average stream flow rate of 1.2 m^3 s^{-1}. The study site had an average daily temperature of 13.1°*C* and experienced four distinct seasons. Silty clay loam soils in the watershed produced fine sediments ($d = 20$ μm, where d is the average particle diameter) from the watershed's landscape that were a significant component of the transported sediment load in the streams (Fox et al., 2014). During the study period, the South Elkhorn watershed had 53 perennial stream reaches: 27 first order, 13 s order and 13 third order.

3. Methods

3.1. Empirical mode decomposition of the carbon time-series

The authors monitored carbon dynamics in the agroecosystem stream using an eight-year dataset of transported sediment carbon that was subsequently post-processed with empirical mode decomposition time-series analysis (Ford and Fox, 2014a; Ford et al., 2015a, 2015b). Briefly, the authors collected transported sediment samples from the outlet of the study watershed on a weekly basis (Fig. 1) utilizing *in situ* sediment traps (Phillips et al., 2000). The authors processed all samples at the University of Kentucky Hydraulics Laboratory by decanting, centrifuging, freezing, and freeze-drying to remove remaining water. The bulk freeze-dried samples were sub-sampled depending on mass; wet-sieved to retain the fines fraction; ground and weighed into silver capsules; and acidified with 6% sulfurous acid to remove carbonate phases (Verardo et al., 1990; Ford and Fox, 2014a). Transported sediment samples were analyzed for elemental compositions of fine particulate organic carbon ($C_{FPOC\text{-}T}$) and its isotopic signature ($\delta^{13}C_{FPOC\text{-}T}$) by combusting samples at 980 °C on a Costech 4010 Elemental Analyzer and then passing the gas stream through a Gas Chromatograph (GC) column (3 m HS-Q) to a Thermo Finnigan Delta-Plus XP Isotope Ratio Mass Spectrometer (IRMS).

The authors performed empirical mode decomposition of the eight-year sediment carbon dataset using a time-series analyses outlined in Ford et al. (2015b). In the present study, the authors emphasize the long-term residual trends from empirical mode decomposition (EMD), which have not been discussed previously, in order to study long-term sequestration of carbon via algal stabilization. Empirical mode decomposition is a non-linear, non-stationary time-series analysis method that decomposes a dataset into a series of intrinsic mode functions, or IMFs (Huang et al., 1998; Wu et al., 2007). IMFs are a finite series of amplitude and frequency modulated, oscillatory functions in which the lowest frequency intrinsic mode function is the base trend and the highest frequency trend is considered noise for well-sampled datasets (Wu et al., 2007). As discussed in Ford et al. (2015b), the authors performed empirical mode decomposition using a six step iterative procedure in which the dataset $X(t)$ was represented as:

$$X(t) = \sum_{i=1}^{n} c_i + r_n$$

where, c_i were the IMFs, and r_n was the residual noise following the coarsest frequency trend. The coarsest frequency trend was the particular trend of interest for the current work.

3.2. Deterministic modeling of stream carbon dynamics

The authors applied the **Iso**tope-based **Fl**uvial **O**rganic **C**arbon, or *ISOFLOC*, numerical model to further investigate the prevalence of algal stabilization and its governing processes. *ISOFLOC* is a process-based stream C model that simulates both terrestrial and autochthonous carbon fate and transport within the stream corridor. Additionally, ISOFLOC simulates multiple dissolved and particulate carbon pools and their transformations. Ford and Fox's study (2015) details *ISOFLOC*'s model formulation, sensitivity, and calibration procedure and provides a detailed list of inputs and parameters with justified ranges for application of *ISOFLOC* specific to the South Elkhorn watershed. In the next paragraphs, the authors provide a brief synopsis of *ISOCFLOC*'s description and applicability to simulate algal stabilization.

ISOFLOC includes water and sediment transport subroutines that