Influence of run of river dams on floodplain sediments and carbon dynamics

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Abstract

Quantifying the biophysical impacts of management on river and stream ecosystems is an important issue that requires understanding of ecological, hydrological and geomorphological processes. We conducted a year-long ecogeomorphological experiment to determine sedimentation and carbon cycling differences between run-of-river (ROR) dams in a 200 year old impounded floodplain and a floodplain that was formerly impounded > 65 years ago. Our study shows that ROR dams do not necessarily enhance floodplain sedimentation or carbon storage, but promote brief periods of sediment CH₄ flux (up to 2.91 nmol CH₄ m⁻² s⁻¹) to the atmosphere. Removal of a ROR dam may result in channel widening, and removal by lateral transport (i.e., erosion) of nearly 14 MgC per floodplain. We did not find significant differences in mean sediment CO₂ fluxes or temperature sensitivity ($Q_{10} = 2.1 \pm 0.4$) of CO₂ efflux among floodplains. All floodplains were likely an annual net source of sediment CO₂ flux (annual mean of $2.12 \pm 0.974 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) to the atmosphere, and a sink for atmospheric CH₄ (annual mean of $-0.221 \pm 0.163 \text{ nmol CH}_4 \text{ m}^{-2} \text{ s}^{-1}$). We provide a conceptual model on the management consequences on ROR dam structures for floodplain sedimentation/erosion, and sediment carbon cycling.

Keywords: floodplain, sediment respiration, dams, methane, greenhouse gases, stratigraphy, geomorphology

1. Introduction

Large reservoir dams have been shown to be a source of CH₄ to the atmosphere (Galy-Lacaux and Delmas, 1997; Rosa et al., 2004; Teodoru et al., 2012), to promote the breakdown of excess nutrients due to long water residence times (Parekh and Mccully, 2004), and to enhance the storage of sediment (Annandale, 2006) and organic matter (Li et al., 2014). In contrast, little information on carbon dynamics and sedimentation of smaller run-of-river (ROR) dams is available. Run-of-river dams may exert a significant influence on landscapes because these structures can be substantially older (one to two centuries) and more numerous (10 to 1) than larger reservoir dams (Csiki and Rhoads, 2010). No studies have been conducted on the impact of ROR dams on the production of greenhouse gas (GHG) fluxes from floodplain sediments, and very few studies have been conducted on the storage of carbon within floodplain sediments (Wang et al., 2014). Recent work on floodplain sedimentation disagrees about the level of anthropogenic enhancement of the storage of sediments within floodplains (Donovan et al., 2015; Hupp et al., 2013; Merritts et al., 2011; Walter and Merritts, 2008). The majority of studies related to ecosystem processes and ROR dams focus on responses to the removal of the dams with little documentation of how existing ROR dams influence carbon dynamics (Gangloff, 2013; Stanley and Doyle, 2003; Tullos et al., 2014). Due to the increasing awareness of ecosystem management on carbon dynamics it is important to properly quantify the effects of ROR dams and their removal across different ecosystems.

Floodplains across different ecosystems have been documented as a net source of CO₂ (Batson et al., 2014; Jacinthe, 2015), a net sink of CH₄ to the atmosphere (Jacinthe, 2015; Segers, 1998), and have the potential to store carbon (up to 0.22 kg C m⁻²yr⁻¹) in their sediments (DeLaune and White, 2012; Kayranli et al., 2010). Floodplains typically receive sporadic inputs

of sediment and nutrients during overbank floods that further enhance and promote the storage of carbon, production of CO₂, and consumption of CH₄ (Craft and Casey, 2000; Nanson and Croke, 1992; Pizzuto et al., 2008). Studies have shown that the frequency and duration of wetting of floodplains can alter biogeochemical processes (Altor and Mitsch, 2006; Jacinthe et al., 2015; Pacific et al., 2009), and rewetting events substantially influence soil gas fluxes to the atmosphere (Kim et al., 2012). Typically, ROR dams fail to flood the valleys they impound and therefore impounded segments retain a stream-like morphology rather than being converted to a lake (Csiki and Rhoads, 2010; Juracek, 1999). The retention of a fluvial morphology leads to depositional patterns that are similar to a pre-impoundment regime, including bedload stored within the channel and overbank sediments deposited on the floodplain. Furthermore, the water table upstream of the ROR dams is kept artificially elevated potentially creating anoxic conditions influencing the biogeochemistry of floodplain sediments.

Dam removal has increasingly become an ecological tool for the restoration of rivers in recent decades (Csiki and Rhoads, 2010; Stanley and Doyle, 2003); however, the consequences of removing a dam from a stream are varied and depend on the regional setting (Doyle et al., 2003b; Pizzuto, 2002; Skalak et al., 2011). Generally, a stream will incise into stored sediment in the channel, perhaps even initiating a knick point, (Sawaske and Freyberg, 2012) and eventually the stream will widen to some degree into the banks of the channel (Major et al., 2012; Pearson et al., 2011; Sawaske and Freyberg, 2012). Later, the stream finally adopts a form that is quasi-stable under the post-removal flow and sediment regime. The extent and timing of incision and widening is poorly constrained and is currently being actively debated (Donovan et al., 2015; Hupp et al., 2013; Merritts et al., 2011; Walter and Merritts, 2008).

The goal of this study is to document the ecogeomorphological differences between pairs of floodplains on the same river that have experienced similar land use, are located within the same climatic region, and generally have a similar vegetation pattern. The key difference between these two pairs of floodplains is that the first pair has a 200 year old impounded floodplain and the second pair has a floodplain that was initially impounded 200 years ago but was breached at least 65 years ago. We show how the resulting geomorphological differences influence ecosystem processes (e.g., GHG fluxes and carbon storage). We propose two main hypotheses. The first is related to the geomorphology and stratigraphy of floodplains: H1- ROR dams increase sedimentation upstream of the dam and facilitate thicker floodplain sequences than would otherwise be present, and the removal of a dam without replacement over the long term allows some but not all of the accumulated sediment to be eroded. The second hypothesis is related to the ecosystem processes and is split into two parts. The first part deals with the long-term impacts (i.e., decadal): H2a- impounded floodplains store more carbon than non-impounded floodplains. The second part deals with current processes (i.e., <1 year): H2b - impounded floodplains are a source of methane (CH₄) likely due to flooding and anoxic conditions, whereas all other floodplains are a sink for CH₄; removed-dam floodplains are a larger source of carbon dioxide (CO₂) compared to other floodplains, likely as a result of higher rates of organic matter decomposition that could have been accumulated during the impounded period. We test these hypotheses by describing the geomorphology and stratigraphy of floodplains and through measurements of sediment GHG fluxes, sediment temperature, sediment moisture, sediment carbon and nitrogen, and biomass accumulation in paired floodplains.

2. Materials and methods

The study area is located in northeastern United States, in northern Delaware (Fig. 1) within the Red Clay Creek (140 km²) watershed, a tributary to the Christina River and ultimately the Delaware River estuary. The study sites are located along an alluvial-bedrock channel (Howard, 1998; Turowski et al., 2008) with mixed sand and gravel bed material and frequent pools and riffles, well-developed narrow floodplains, cohesive silty banks (Jacobson and Coleman, 1986; Walter and Merritts, 2008), and temperate forested riparian zones. Our study area within the Christina River basin lies just north of the Fall Line (Renner, 1927) within the Piedmont physiographic province (Fischer et al., 2004). The Christina River basin has 7.8% impervious surfaces and a population density of 1764 per km². The basin is 30% developed, 32% forested, and 37% agricultural (Kauffman et al., 2008). The underlying bedrock consists of Cambrian metamorphic rocks of the Wissahickon Formation (Schenck et al., 2000) and Ordovician metamorphic rocks of the Faulkland gneiss and Windy Hill gneiss (Schenck et al., 2000). Intense precipitation events are usually delivered by thunderstorms, hurricanes or nor'easters. The mean annual precipitation in the watershed is 115.56 cm year⁻¹ with a mean annual temperature of 12.7°C.

The Christina River basin experienced massive deforestation during colonial times as forests were clear-cut for agriculture. Construction of ROR dams began as early as 1802 when the DuPont family settled in the area (Kauffman et al., 2008). At the height of ROR dam construction, there may have been hundreds of operating ROR dams in the watershed (Walter and Merritts, 2008), but only 72 ROR dams are currently in place in the subwatersheds of the Christina River, Brandywine River, White Clay Creek, Red Clay Creek and Naamans Creek (Kauffman et al., 2008).

We focus on two ROR dams, the Barley Mill Road (BMR) dam and the former Fell Spice Mill (FSM) dam. These dams are located within 3 km from each other so they are subject to similar climatic variability and mean annual temperature (23.1°C) and total annual precipitation (84.4 cm). The BMR dam is still in place, located along Barley Mill Road (Fig. 1) and featured an old slitting and rolling mill (i.e. a mill for processing iron rods) that was in operation from 1814-1918 (Delaware Department of Transportation, 2003). Following its active use, the BMR dam was stabilized with concrete and it remains intact. The FSM dam featured a spice mill that started operation in 1828 and failed sometime before 1950 along with the dam. The former location of the FSM dam is upstream of where Faulkland Road crosses the Red Clay Creek (Fig. 1).

The floodplain vegetation at the BMR site differs between the upstream impounded floodplain and the downstream non-impounded floodplain. The BMR upstream floodplain vegetation is dominated by grasses and nettles with few tall trees. The BMR downstream floodplain vegetation is dominated by bushes and tall trees. The FSM floodplains have similar woody bush and tall trees on both the upstream formerly impoundment floodplain and downstream non-impounded floodplain.

2.1. Sampling design

The data collected allowed us to look at both the long-term (i.e., decadal) impacts and current short-term (i.e., <1 year) responses of dam building and removal. Long-term impacts were assumed to be recorded within the sediment column of the floodplains such as the amount of carbon and nitrogen stored at depth, and geomorphological information connected to dam

building. Short-term responses were measured bi-weekly and include sediment GHG fluxes, sediment moisture, sediment temperature, and biomass collections.

Our field measurements focused on the floodplains immediately upstream and downstream of each ROR dam (former in the case of FSM). We established three cross sections per floodplain (total of 12 cross sections) perpendicular to the flow of the stream. Cross sections were subdivided into three distinct zones based on distance from the channel. The near floodplain was the zone of the floodplain immediately adjacent to the channel. The far floodplain was the zone of the floodplain furthest from the channel before the toe of the hillslope. The middle floodplain was the zone between the near and far floodplain. A single location for sampling was located along each cross section within each of the three zones (36 sampling locations). Sampling locations served as the sites for a suite of measurements designed to characterize the impact of ROR dams on floodplain carbon dynamics.

2.2. Measurements of long-term impacts

Coring at sampling locations was performed with a 1-1/2' gouge auger that was driven until refusal (defined as the point to which the coring device cannot be driven any further, typically as a result of encountering large rocks, a gravel layer, or extremely dense sediment). Core descriptions were logged in the field and samples were taken for sediment bulk density, total carbon, and total nitrogen from different compositional layers in each core. Stratigraphy down core was assessed by compositional variations and color was determined with a Munsell Color Chart. We used five compositional categories based on grain size estimated from cores (using grain-size terminology of the Wentworth scale; Wentworth, 1922). The term gravel applies to a layer with >50% gravel or indicates refusal on rocks and gravel. The term sand

175 applies to a layer with 90-100% sand and 0-10% mud. The term muddy sand applies to a layer
176 with 60-80% sand and 20-40% mud. The term sandy mud applies to a layer with 20-40% sand
177 and 60-80% mud. Lastly, the term mud applies to a layer with 0-10% sand and 90-100% mud.
178 For the purposes of our grain size categories, mud includes both the silt and clay fraction as they
179 cannot be distinguished in the field. Apart from compositional categories extensive mottling at
180 depth was also identified in the field as a distinct characteristic. We assume that extensively
181 mottled layers may mark potentially persistent water table elevations at depth. Sediment samples
182 were dried in an oven at 45°C and analyzed for bulk density before being processed for total
183 carbon and total nitrogen using a CHNS Elemental analyzer (vario MICRO cube, Elementar
184 Americas Inc., Mt. Laurel, NJ). We calculated total carbon down core by first using measured
185 representative bulk density to convert volumes of the core to mass based on the depth intervals of
186 the bulk density measurements. The down core volumes were then multiplied by the measured
187 percent carbon. The average of nine cores was use to give a mean total mass of carbon stored at
188 depth per floodplain.

189 Topographic cross sections were surveyed with a total station or constructed using a
190 combination of Trimble GeoXH to ascertain location and topographic map data provided by
191 New Castle County (2-foot (i.e., 0.61 m) contour interval; State of Delaware, 2008) to determine
192 elevation. Cross sections were used to correlate coring data within cross sections in addition to
193 determining depth of floodplains. Recent aerial photography was also used to calculate an
194 average width of each section of stream, upstream and downstream of the dam, to try and
195 determine if the removal of the FSM had any influence on width adjustment over time. The
196 average widths of stream sections were determined by taking the perimeter of the active stream
197 channel and dividing by the length of the stream section. Trimble surveys were conducted during

the months where trees had no leaves (November 2014 and April 2015) and the Trimble TerraSync software (Trimble, Sunnyvale, CA) was used to download the data and provide an estimate of the error.

2.3. Measurements of short-term responses

Litter biomass from the soil O-horizon was sampled at all 36 sampling locations (Fig. 1) during the beginning (May), peak (August), and end (October) of the 2014 growing season. The entire O-horizon was collected from within a 0.30 m x 0.30 m area, oven dried at 45°C for 72 hours, and then weighed in order to calculate the dry mass (i.e., litter biomass in g m⁻²). Superficial (10 cm depth) sediment samples were collected using a 2.5 cm push core to measure pH (HI 99121; Hanna Instruments) at the same time as the O-horizon collection.

Sediment GHG fluxes (i.e., CO₂ and CH₄ fluxes) were measured every two weeks using an Ultraportable Los Gatos Greenhouse Gas Analyzer (Los Gatos Research, Santa Clara, CA), hereafter LGR. This instrument can measure CH₄ concentrations from 0.01 to 100 ppm ± 0.002 ppm at 1 Hertz. In addition, the LGR can measure CO₂ concentrations from 1 to 20000 ± 0.3 ppm at 1 Hertz. A 15 cm diameter PVC collar was permanently installed at each sampling location at 5 cm depth 14 days before measurements started (36 total collars, 9 per floodplain). We measured GHG fluxes using a closed system where the vacuum pump of the LGR was attached to a chamber that allowed gases to accumulate for 3 minutes to record (2 second response) the change in concentration within the chamber. Therefore, the GHG flux at each sampling location was calculated using 180 measurements and fitting the following equation (Pumpanen et al., 2004):

$$fCx = \left(\frac{dC}{dt} \right) \left(\frac{V_c}{A_c} \right) \left(\frac{P}{R * (T_s + 273.15)} \right) \quad (1)$$

where fCx is the efflux of a GHG (CO_2 or CH_4), dC/dt is the change in concentration with time measured by the LGR (ppm s^{-1}), V_c is the system volume (i.e., LGR + soil chamber; 0.01795 m^3), A_c is the area of the chamber (0.018 m^2), P is atmospheric pressure ($101.325 \text{ kg m s}^{-2}$), R is the ideal gas law constant ($0.00831447 \text{ kg m}^2/\mu\text{mol K s}^2$), T_s is the measured sediment temperature ($^{\circ}\text{C}$), and 273.15 is the conversion to degrees Kelvin. In addition to biweekly measurements of T_s we measured sediment moisture at 5 cm depth (WET-2, Delta-T Devices, Cambridge, UK). We report sediment gas fluxes for both CO_2 ($\mu\text{mol m}^{-2} \text{ s}^{-1}$) and CH_4 ($\text{nmol m}^{-2} \text{ s}^{-1}$) as a monthly average of the bi-weekly measurements for each sampling location.

The potential relationship between CO_2 or CH_4 with soil temperature were analyzed using an exponential equation:

$$fCx = \beta * e^{(\alpha * T_s)} \quad (2)$$

where fCx is the efflux of a GHG (CO_2 or CH_4), β and α are regression coefficients, and T_s is the sediment temperature. The temperature sensitivity (Q_{10}) and its 95% confidence intervals (CI) were calculated using:

$$Q_{10} = e^{10 * \alpha} \quad (3)$$

where α is the regression coefficient obtained from equation (2). The 95% CI were calculated using the upper and lower 95%CI of α derived from equation (2). Similar approaches to calculate 95%CI for Q_{10} values have been reported previously (Vargas et al., 2012).

Fifteen-minute discharge data during the entire study period was acquired from USGS Gaging station 01480000 Wooddale at Red Clay Creek (Fig. 1), and precipitation data during the entire study period was acquired from the Mt. Cuba weather station in Hockessin, DE (Fig. 1).

Data were analyzed using a repeated ANOVA using time and sampling location as fixed factors. If significant differences were found ($\alpha = 0.5$) then a Tukey-Kramer *post hoc test* was applied to identify differences among the treatments.

3. Results

3.1. Geomorphological surveys and sediment cores

3.1.1. Stratigraphy

Floodplain cores show that both downstream floodplains at BMR and FSM have a similar stratigraphic sequence. The near floodplain locations are predominantly sand and far floodplain locations are primarily mud (Figs. S1 and S2). The middle floodplain locations are a mixture of sand and mud, typically alternating between muddy sand and sandy mud. Both downstream floodplains also have a distinct mottled layer before refusal (Figs. S1 and S2). Refusal in the downstream locations was predominantly a gravel layer (Figs. S1 and S2).

The floodplain upstream of the BMR dam has a large amount of sand at the surface of the near floodplain locations (Fig. S3) with mud content increasing towards the far floodplains. The middle floodplains generally consist of muddy sand and sandy mud and the far floodplains generally transition to mud. The near floodplain at depth transitions from sand to muddy sand before refusing on gravel (Fig. S3). At depth the middle floodplain is a complex interfingering of sandy muds and muddy sands that refuse on gravels (Fig. S3). The far floodplain is typically mud or sandy mud and refusing on gravel (Fig. S3). There are two layers of mottling, 1) about 1 m depth in the middle and 2) directly above refusal, which is approximately 2.5 – 3 m deep (Fig. S3).

The floodplain upstream of the former FSM dam lacks the large sandy levee deposits at the near floodplains and instead has interbedded layers of sandy mud and muddy sand to refusal which is a gravel layer (Fig. S4). Both the middle floodplains and far floodplains are capped with mud layers that are underlain by sandy mud, typically mottled. Finally, refusal at the middle and far floodplains is a mud layer that is too dense to core through (Fig. S4).

3.1.2. Floodplain depths and stream widths

The geomorphic cross sections in conjunction with the sediment cores show that the average depth of the upstream BMR floodplains is thicker than the three other floodplains studied with an average depth of 210 cm (Table 1); however, the upstream floodplains are not substantially thicker than their downstream counterparts. Aerial photography shows that the upstream and downstream average stream width of the BMR site is 23.2 and 23.1 m respectively, whereas the upstream and downstream average stream width of the FSM site is 23.9 and 20.0 m respectively. Given the similar widths upstream and downstream of the BMR dam, the lack of similarity between the upstream and downstream FSM dam may represent an approximate widening of ~4 m.

3.1.3. Sediment properties, total carbon, and total nitrogen

The pH of the sediment at the upstream floodplain of BMR was 6.12 (± 0.33), the downstream floodplain at BMR was 6.28 (± 0.28), the upstream floodplain at FSM was 5.50 (± 0.37), and the downstream floodplain at FSM was 6.28 (± 0.28). There was no statistical difference between the pH of upstream and downstream floodplains at BMR; however there was

a statistical difference between the pH of upstream and downstream floodplains at FSM (ANOVA, $F = 49.76$, $p < 0.001$).

Sediment cores show that the floodplains at BMR store more carbon and nitrogen with depth than the floodplains at FSM (ANOVA, $F = 12.52$, $p = 0.001$; based on Tukey-Kramer test), but there is no statistical difference between the upstream and downstream floodplains at BMR nor the upstream and downstream floodplains at FSM (Figs. 2 and 3). The total carbon stored in an average cross section in each floodplain is 80 ± 41 MgC for the upstream BMR, 58 ± 8.4 MgC for the downstream BMR, 66 ± 40 MgC for the upstream FSM, and 17 ± 6.8 MgC for the downstream FSM (Table 1; Table S1-S5).

3.2. Hydrologic data

The climatological data acquired from the USGS gaging station at Wooddale (014008000) and the Mt. Cuba Weather station (Fig. 1) are shown in Fig. 4. The large peak in both discharge and precipitation occurred on the night of April 30, 2014 and is the fifth largest flood recorded at Wooddale and corresponds to a 15 year flood based on the Log-Pearson III analysis (Pearson and Pizzuto, 2015). The discharge event flooded three of the four floodplains in our study and removed three of the gas chamber collars during the event, which were later replaced. The absence of newly deposited sediment and the undisturbed leaf litter at the upstream floodplain of the FSM site suggest that the river did not flood this area.

3.3. Sediment GHG fluxes

3.3.1. Temporal variations in GHG fluxes

The overall mean of sediment CO₂ flux across floodplains is $2.12 \pm 0.97 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. The sediment CO₂ flux exhibits a similar temporal pattern among three of the four floodplains (BMR upstream, BMR downstream, and FSM downstream), starting at or near zero $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ for the month of April, increasing towards peak output in June ($4.13\text{--}4.55 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) before leveling off through July and August ($3.09\text{--}4.09 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), steadily decreasing towards zero over September and October, and finally reaching zero or near it in November. The FSM upstream floodplain exhibited a slightly different CO₂ flux trend, with an increasing rate of efflux until September before falling towards zero similar to the other three floodplains. The FSM floodplains have lower variability of CO₂ flux across all months of sampling than the BMR floodplains, with the FSM upstream floodplain having the lowest (i.e., coefficient of variation; CV = 0.52; Fig 5). The downstream BMR floodplain has the greatest variability among the four floodplains (CV = 0.78; Fig. 5).

The overall mean of sediment CH₄ flux across floodplains is $-0.22 \pm 0.16 \text{ nmol CH}_4 \text{ m}^{-2} \text{ s}^{-1}$ however, the CH₄ flux patterns differ between BMR and FSM floodplains. Both FSM floodplains act as sinks the entire eight months and exhibit very similar rates (Fig. 5). Both BMR floodplains exhibit a spike in CH₄ flux up to $2.91 \text{ nmol CH}_4 \text{ m}^{-2} \text{ s}^{-1}$ (Fig. 5) during the month of May, and elevated CH₄ flux continued into the month of June for the upstream BMR floodplain before both floodplains became sinks for CH₄ once more (Fig 5). Once again the FSM floodplains exhibit the lower variability across the sampling period, however, the downstream FSM floodplain has the lowest variability (i.e., coefficient of variation) with regards to CH₄ flux (CV = 0.68; Fig 5). The upstream BMR floodplain has the largest CH₄ flux (CV = 3.8; Fig 5).

The sediment temperature and sediment moisture among all four floodplains exhibits nearly the same pattern during the eight-month study, decreasing across the study period.

Sediment temperature and moisture have similar values and temporal trends across all four floodplains (Fig. 5).

3.3.2. Relationship between sediment GHG fluxes and floodplain sampling location

Upstream of the BMR Dam the sediment CO₂ flux is highest near the stream (ANOVA, $F = 10.25$, $p < 0.001$, based on Tukey-Kramer test) and has similar magnitude in the middle and far floodplains (Fig. 5). Downstream of former FSM Dam the far floodplain has the highest sediment CO₂ flux (ANOVA, $F = 9.77$, $p < 0.001$; based on Tukey-Kramer test) with the near and middle floodplains having similar magnitudes (Fig. 5). The sediment CO₂ flux is not statistically different among all floodplain locations both downstream of BMR Dam and upstream of the former FSM Dam (Fig. 5).

The far floodplain both upstream and downstream of BMR Dam seems to be different with respect to CH₄ flux than the near and middle floodplains (Fig. 5); however, only the upstream far floodplain of BMR Dam sediment CH₄ flux is statistically different from the upstream BMR near and middle floodplain locations (ANOVA, $F = 11.13$, $p < 0.001$; based on Tukey-Kramer test). All locations of both floodplains of the former FSM Dam are sinks of CH₄ and are not statistically different from each other (Fig. 5).

Sediment temperatures among all sections of all floodplains are statistically similar (Fig. 5). Far floodplains are generally the wettest sections of the floodplains and the near floodplains are the driest (Fig. 5). Spatial differences in sediment moisture on the upstream floodplain of the former FSM Dam are not statistically different.

3.3.3. Relationship between GHG and sediment moisture and sediment temperature

The sediment temperature at both sites was positively correlated with sediment flux of CO₂ with an exponential fit $y = 0.45 * e^{0.074x}$ and $y = 0.41 * e^{0.084x}$ and an r^2 value of 0.69 and 0.83 for the BMR site and FSM site respectively (Fig. 6). The BMR site has a Q₁₀ of 2.10±0.6 (95% CI) and the FSM site has a Q₁₀ of 2.31±0.7 (95% CI), so no differences were found in Q₁₀ between sites. Sediment temperature had no correlation with CH₄ flux, and sediment moisture at both sites had no correlation with CO₂ flux (Fig. 6). Sediment moisture was linearly correlated with CH₄ flux with an r^2 value of 0.43 and 0.38 for the BMR site and FSM site, respectively (Fig. 6). Significant trends are reported for p-values <0.05.

3.4. Soil O-horizon biomass data

The overall averaged biomass of the upstream floodplain at the BMR site had an increasing trend over the course of the monitoring experiment (Fig. 7), while the overall averaged biomass of the downstream floodplain at the BMR site decreased towards the middle of the experiment and ended with more biomass than it started the experiment with (Fig. 7). The averaged biomass of the upstream floodplain at FSM site remained relatively constant the entire experiment (Fig. 7), while the downstream floodplain at FSM had a large increase towards the middle of the experiment and decreased towards the end (Fig. 7). Biomass data are averaged for each collection period and reported with a 95% CI.

4. Discussion

Dam building and dam removal alters adjacent floodplain morphology, which in turn modifies long- and short-term ecosystem processes. We estimate, based on our geomorphic survey data and aerial photographic analysis, that the removal of the FSM Dam may have caused

erosion of previously stored material up to at most 2800 m³. We base this estimate on the average depth of the upstream FSM floodplains (~1.4 m), an average length of impounded floodplain (1000 m), and a conservative estimate of widening due to the removal of the FSM dam (~2 m). Assuming that the estimated material lost with dam removal is 2800 m³, then based on the carbon present currently within the floodplain the removal of the dam may have resulted in a carbon loss of nearly 14 Mg C. Sediment cores show that downstream floodplains from both sites exhibit similar depositional patterns of mostly sand near the channel, mostly mud far from the channel and a mixing in the middle part of the floodplain. The upstream BMR floodplain exhibits a more even distribution, both vertically and horizontally, of sand throughout the floodplain. Lastly, sediment GHG flux measurements show that all floodplains are a source of CO₂ to the atmosphere, act as sinks for CH₄, and an impounded floodplain is capable of becoming a sporadic source of CH₄ to the atmosphere for at least for up to two months following a flood event.

4.1. Sediment storage and floodplain carbon

Floodplains upstream of the dams in our study do not statistically store more sediment than the downstream floodplains similar to the work of Hupp et al. (2013). This is contrary to our initial hypothesis and the work of others (Merritts et al., 2011; Schenk and Hupp, 2009; Walter and Merritts, 2008). Despite the lack of more sediment, run-of-river (ROR) dams do seem to increase the amount of sand present in the floodplains upstream of dams both laterally and vertically as evidenced by the large levee deposits at the near floodplain location and the presence of sand in the far floodplain location of the BMR site. In contrast, the downstream

floodplains typically have mostly sand in the near floodplains in a typical levee deposit, a mix of sand and mud in the middle floodplains, and mostly mud in the far floodplains.

Removal or breaching of a ROR dam may be followed by channel widening into floodplain deposits. The formerly impounded upstream floodplain at FSM lacks characteristic levee deposits that are present at the BMR site. The high level of sand content typically stored near the channel may have provided easily erodible material. The upstream section at FSM is ~4 m wider than its downstream counterpart suggesting that the stream may have experienced widening after the removal of the dam. Assuming that the upstream floodplain at FSM once had a similar level of stored carbon per cross section as the upstream floodplain at BMR currently stores, then the widening after removal of the dam has transported nearly 14 MgC laterally through erosion processes. Widening is a common occurrence after a dam removal (Doyle et al., 2003a; Pizzuto, 2002; Sawaske and Freyberg, 2012). The combination of widening and lowered stream level caused by dam removal has kept the upstream portion of the stream from overtopping its banks. This is evidenced by the lack of disturbance to the floodplain surface following the April 2014 flood, which was a 15 year event for the watershed and was the fifth largest flow since 1943. The widening of the stream after removal has also likely removed what would have been the FSM near floodplain and instead the middle floodplain is currently closest to the channel.

Floodplains upstream of dams do not store more total carbon and total nitrogen per m² than downstream floodplains, similar to sediment storage. Statistically the pair of BMR floodplains store more carbon and nitrogen than the pair of FSM floodplains; however, there is no statistical difference between the upstream (impounded) and downstream (non-impounded) floodplains at either the BMR or the FSM. The formerly impounded floodplains do not maintain

their storage of carbon and nitrogen as the stream erodes into previously stored materials so the net loss of carbon is due to lateral movements due to erosion processes. Furthermore, we postulate that the drop in water table could expose labile carbon that could be rapidly decomposed by microbial metabolism (Fontaine et al., 2004; Qiao et al., 2014) resulting in larger carbon losses during the first years after ROR dam removal.

4.2. Sediment temperature and sediment moisture

The presence, absence or removal of ROR dams has no effect on surface sediment temperature, likely because vegetation cover was similar between sites and the high water content in sediments of the floodplains that acted as a temperature buffer.

Surface sediment moisture data shows that ROR dams enhance the floodplain soil moisture levels and maintain higher levels of sediment moisture than downstream floodplains. In stark contrast, the near floodplain location of all four floodplains always had low levels of sediment moisture due to the high levels of sand. The BMR upstream floodplain, predominately the far floodplain, was kept fully inundated for the entire month of May and parts of June after the April 2014 flood, a phenomenon not repeated at any other floodplain location. The increased stream level upstream of the dam prevents the floodplains from drying out as rapidly as would be expected for Mid-Atlantic floodplains (Batson et al., 2014) and has substantial influence on the dynamics of GHG efflux (Bodelier et al., 2012; Kayranli et al., 2010; Whalen, 2005).

4.3. Sediment CO₂ fluxes

All floodplains in our study, regardless of relationship to ROR dams, have similar sediment CO₂ flux rates, contrary to our hypothesis (Fig.5). We had expected the formerly

impounded upstream floodplain at FSM to be the largest source of CO₂ flux to the atmosphere due to the availability of previously stored carbon. We postulate that during initial dewatering after dam breaching the FSM floodplain became a large source of CO₂ when much of the stored carbon was accessible, and afterwards the levels of CO₂ production returned to normal once the liable carbon had been consumed. As it has been at least six decades since the FSM was in place it is likely that any stored carbon from previous damming had been consumed in this time.

Changes in temperature dependency (i.e., Q_{10}) cannot explain the temporal differences in sediment CO₂ flux between sites, but differences could be the result of several factors. First, there are slightly differences in the first constant (β) of equation 2, which could be interpreted as basal respiration. Second, we postulate that spatial heterogeneity (i.e., represented by the CV) should be considered as previous studies have shown important “hot spots” in soil CO₂ flux that can influence the overall mean, the temporal trends, and the annual sums (Leon et al., 2014). The upstream floodplain of FSM did have the lowest variability of all floodplains likely due to the fact that it can no longer be flooded easily because the stream has widened into the stored floodplain sediments and is 2-3 m lower than the top of the bank. This leads to the only inputs into the system from leaf litter and the atmosphere, whereas all other floodplains have higher variability, likely due to flooding bringing in an influx of dissolved organic matter and solid organic matter along with leaf litter and atmospheric deposition. Therefore, continuous measurements and longer records are needed to fully capture the temporal dynamics of sediment CO₂ dynamics (Vargas et al., 2011).

4.4. Sediment CH₄ fluxes

Our hypothesis regarding CH₄ flux was partially confirmed as currently impounded floodplains source CH₄ when they become inundated as the upstream floodplain at BMR did after the flood of April 2014. We also found that downstream floodplains experience a spike of CH₄ flux when inundated; however, only impounded floodplains were statistically a source of CH₄ flux. Additionally, the impounding promoted a longer CH₄ spike because the ROR dam keeps the water table artificially higher than it would normally be and maintains a higher level of floodplain saturation. It is widely known that extended periods of high levels of sediment moisture allows sediment biogeochemistry to switch from an aerobic dominated regime to an anaerobic dominated one increasing CH₄ production (Segers, 1998). Yet despite the extended saturation, all floodplains in our study are net sinks for CH₄ when averaged over the entire study period with similar fluxes reported for temperate forest ecosystems (Bodelier et al., 2012)

4.5. Conceptual model of run-of-river dam influence on floodplain construction and carbon cycling

Combining our geomorphologic and stratigraphic data with our biogeochemical measurements we propose a conceptual model for the influence of ROR dams on floodplain sedimentation and carbon cycling (Fig. 8). Our conceptual model attempts to demonstrate the influence of a ROR dam based on stages of a dam's life span. Initially, after a ROR dam is first built, some portions of the upstream floodplain are continuously flooded. Sediment and organic matter begins to accumulate rapidly as the upstream floodplain accretes based on the newly elevated water level upstream of the dam. The floodplain downstream of the dam is likely cut off from the upstream sediment supply for some amount of time and sediment inputs to the downstream floodplain are likely lessened (Fig. 8a).

Next, the upstream flood plain is no longer continuously flooded anywhere; however, the upstream floodplain continues to accumulate sediment as overbank accretion is easier to achieve in a dammed state. Sediment transport over the dam has likely restored input of sediment to the downstream floodplain (Pearson and Pizzuto, 2015). Sediment and organic matter are added to both upstream and downstream floodplains at similar rates (Fig. 8b).

For the purposes of our conceptual model, there exist two options that can befall a dam: it can continue to exist (Fig. 8c) or it can be removed/breached (Fig. 8d). In the case of continued damming (Fig. 8c) the upstream floodplain continues to receive sediment and organic matter as the floodplain is able to accrete further. The water table is kept artificially elevated in the upstream floodplain.

In the case of removal/breaching (Fig. 8d), the stream level upstream of the former dam falls back to near a pre-dam level, and begins to rework part of the formerly impounded floodplain, likely eroding the highly sandy deposits immediately adjacent to the stream. The downstream floodplain may receive a large influx of sediment but this pulse is typically transitional and short lived (Pearson et al., 2011). Based on the difference between the bank height and stream level upstream of the former dam, streams may not be able to overtop their banks during flood events as easily as they could during damming. This will decrease stream based inputs to the upstream floodplains making the atmosphere and leaf litter the primary inputs to the system.

Floodplain fluxes of CO₂ and CH₄ can be approximated for four different floodplains that represent the potential final condition of our conceptual model (Fig. 8e). All floodplains source CO₂ to the atmosphere and have approximately the same magnitude of CO₂ flux but the formerly impounded floodplain has the lowest magnitude and the lowest variability, while the currently

impounded floodplain has the largest variability and is the second largest magnitude of CO₂ flux. All of the floodplains are net sinks for CH₄ with the impounded floodplain having the highest variability of CH₄ flux due to its time spent as a source of CH₄ while inundated.

5. Conclusions

Our ecogeomorphic study shows that run-of-river dams do not enhance floodplain sedimentation, they promote periods of CH₄ flux to the atmosphere, that the removal of a dam will result in lower storage of total carbon and total nitrogen, and the removal of a dam may facilitate the lateral erosion of up to 14 MgC. Run-of-river dam impacted floodplains receive larger amounts of sediment during overbank events than unimpounded floodplains, and sand is deposited across the entire. Impacted floodplains are also kept inundated for longer periods of time, promoting CH₄ flux during floodplain saturation. Yet despite periods of sourcing CH₄ to the atmosphere, all floodplains in our study were a net sink of CH₄.

Sediment CO₂ fluxes from the formerly impounded floodplain are of similar magnitude to the other floodplains in our study, suggesting that any spike in CO₂ flux from dam breaching is a brief phenomenon related to multiple rewetting events (Kim et al 2012). Furthermore, spatial heterogeneity in sediment CO₂ fluxes should be considered, and continuous measurements are needed to identify the exact timing and magnitude of a potential dam breaching pulse of CO₂ flux (Vargas et al., 2011).

Despite all floodplains acting as sinks for CH₄, it is important to recognize that recent work has suggested that climate change may lead to potentially wetter conditions and more frequent flood events (Bodelier et al., 2012; Perry et al., 2015). Extended wet periods combined with more frequent flooding will likely yield longer periods of CH₄ production from floodplains

536 that are impounded by ROR dams. This could yield a potential positive feedback that could
537 convert impounded floodplains from sinks for CH₄ to permanent sources of CH₄, a process that
538 would have a global scale impact given the global abundance of ROR structures (Liu et al., 2014;
539 Vanmaercke et al., 2015).

540

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737

738 **Tables**

739 Table 1. Sediment depths, cross sectional widths and mass of carbon stored of each floodplain at
 740 the Barley Mill Road (BMR; currently impounded) and Fell Spice Mill (FSM; formerly
 741 impounded) sites.

	Upstream BMR			Downstream BMR		
	XS+3	XS+4	XS+5	XS-1	XS-2	XS-3
Near floodplain depth (m)	3.035	3.02	2.99	2.15	2.03	1.91
Middle floodplain depth (m)	1.88	1.83	2.11	2.16	1.97	1.74
Far floodplain depth (m)	0.89	1.61	1.54	2.04	1.86	1.54
Average depth (m)	1.94	2.15	2.21	2.12	1.95	1.73
Floodplain width (m)	21.4	33.2	43	32.2	42.5	37.8
Floodplain average depth (m)	2.10±0.76			1.93±0.20		
Floodplain average width (m)	32.5±10.8			37.5±5.16		
Mass of Carbon (MgC)	80±41			58±8.4		
	Upstream FSM			Downstream FSM		
	XS+3	XS+2	XS+1	XS-1	XS-2	XS-3
Near floodplain depth (m)	1.99	2.64	2.11	0.65	0.98	0.46
Middle floodplain depth (m)	1.41	1.17	0.93	1.15	1.22	1.21
Far floodplain depth (m)	0.64	0.65	0.90	1.29	1.28	1.18
Average depth (m)	1.35	1.49	1.31	1.03	1.16	0.95
Floodplain width (m)	34.7	22.7	19.4	15.8	22	14.3
Floodplain average depth (m)	1.38±0.71			1.05±0.30		
Floodplain average width (m)	25.6±8.05			17.4±4.08		
Mass of Carbon (MgC)	66±40			17±6.8		

742

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Figure legends

Fig. 1. Study area map for the field experiment. A) Overview of the length of stream studied, including United States Geologic Survey (USGS) gaging station (yellow circle) and Mt. Cuba weather station (star). Barley Mill Road Site, the currently impounded site, is shown in the upper panel and the upstream (B) and downstream (C) floodplains are shown with near, middle and far floodplain locations delineated as well as the sampling locations on the cross sections. Fell Spice Mill site, the formerly impounded site, is shown in the bottom panel and also has the upstream (D) and downstream (E) floodplains with delineated near, middle and far floodplain regions as well as the sampling locations.

Fig. 2. Total nitrogen and total carbon data at depth for the Barley Mill Road site. (A) Percent total nitrogen of 20 mg samples with multiple samples from similar depths averaged together. (B) Percent total carbon of 20 mg samples with multiple samples from similar depths averaged together. (C) Mass of nitrogen per area of depth, and (D) mass of carbon per area of depth for BMR site with multiple samples from similar depths are averaged together to plot one line for upstream floodplain and one line for downstream floodplain. Upstream data are represented by black squares and downstream data are represented by gray squares. Points that had multiple samples at the same depth also have their standard deviation shown.

Fig. 3. Total nitrogen and total carbon data at depth for the Fell Spice Mill site. (A) Percent total nitrogen of 20 mg samples with multiple samples from similar depths averaged together. (B) Percent total carbon of 20 mg samples with multiple samples from similar depths averaged together. (C) Mass of nitrogen per area of depth, and (D) mass of carbon per area of depth for

FSM site with multiple samples from similar depths are averaged together to plot one line for upstream floodplain and one line for downstream floodplain. Upstream data are represented by black circles and downstream data are represented by gray circles. Points that had multiple samples at the same depth also have their standard deviation shown.

Fig. 4. Hyetograph for Red Clay Creek study area from March 1, 2014 to December 31, 2014

Fig. 5. Temporal and spatial patterns related to CO₂ flux, CH₄ flux, sediment temperature, and sediment moisture.

Fig. 6. Sediment temperature and sediment moisture plotted against CO₂ and CH₄ flux for Barley Mill Road and Fell Spice Mill sites. Significant regressions and r² values are shown for significant trends (p < 0.05)

Fig. 7. Averaged biomass data for the four floodplains based on floodplain location and total average for each floodplain. Letters indicate if the different floodplain locations are statistically different. Columns with matching letters indicate no statistically significant difference whereas columns with differing letters indicate a statistically significant difference between locations on the floodplain in question.

Fig. 8. Conceptual model of the influence of run-of-river dams on floodplain construction and carbon cycling based on stages of damming. A) Initial building of the dam and accretion of the upstream floodplain. B) Upstream floodplain is elevated above stream. After elevation of

790 floodplain there are two options that can happen to a dam: C) option 1 continued damming or D)
791 option 2 dam removal/breaching. E) Approximate flux magnitude, direction, and variability for
792 each of the four distinct floodplain ecosystems. Note: OM = organic matter addition, sed =
793 sediment addition, and arrows show magnitude of process relative to the other processes
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Figure 8