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

Adam J. Pearson [a,1], James E. Pizzuto [a], Rodrigo Vargas [b,*]

[a] Department of Geological Sciences, University of Delaware, Newark, DE 19716, USA
[b] Department of Plant and Soil Science, University of Delaware, Newark, DE 19716, USA

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A B S T R A C T

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 CH_4 flux (up to 2.91 nmol CH_4 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 CO_2 fluxes or temperature sensitivity ($Q_{10} = 2.1 \pm 0.4$) of CO_2 efflux among floodplains. All floodplains were likely an annual net source of sediment CO_2 flux (annual mean of 2.12 ± 0.974 μmol CO_2 m^{-2} s^{-1}) to the atmosphere, and a sink for atmospheric CH_4 (annual mean of -0.221 ± 0.163 nmol CH_4 m^{-2} s^{-1}). We provide a conceptual model on the management consequences on ROR dam structures for floodplain sedimentation/erosion, and sediment carbon cycling.

1. Introduction

Large reservoir dams have been shown to be a source of CH_4 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 Mcculy, 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 CO_2 (Batson et al., 2014; Jacinthe, 2015), a net sink of CH_4 to the atmosphere (Jacinthe, 2015; Segers, 1998), and have the potential to store carbon (up to 0.22 kg C m^{-2} yr^{-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 CO_2, and consumption of CH_4 (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.

* Corresponding author.
E-mail address: rvargas@udel.edu (R. Vargas).
[1] Present address: Department of Earth and Atmospheric Sciences, Saint Louis University, St. Louis, MO 63108, USA.

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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 (CH_4) likely due to flooding and anoxic conditions, whereas all other floodplains are a sink for CH_4; removed-dam floodplains are a larger source of carbon dioxide (CO_2) 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 km^2) 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 km^2. 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 to 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 Munsel 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 applies to a layer with 90–100% sand and 0–10% mud. The term muddy sand