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Research Paper

Increasing floodplain connectivity through urban stream restoration increases nutrient and sediment retention

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ABSTRACT

Stream restoration practices frequently aim to increase connectivity between the stream channel and its floodplain to improve channel stability and enhance water quality through sediment trapping and nutrient retention. To measure the effectiveness of restoration and to understand the drivers of these functional responses, we monitored five restored urban streams that represent a range of channel morphology and restoration ages. High and low elevation floodplain plots were established in triplicate in each stream to capture variation in floodplain connectivity. We measured ecosystem geomorphic and soil attributes, sediment and nutrient loading, and rates of soil nutrient biogeochemistry processes (denitrification; N and P mineralization) then used boosted regression trees (BRT) to identify controls on sedimentation and nutrient processing. Local channel and floodplain morphology and position within the river network controlled connectivity with increased sedimentation at sites downstream of impaired reaches and at floodplain plots near the stream channel and at low elevations. We observed that nitrogen loading (both dissolved and particulate) was positively correlated with denitrification and N mineralization and dissolved phosphate loading positively influenced P mineralization; however, none of these input rates or transformations differed between floodplain elevation categories. Instead, continuous gradients of connectivity were observed rather than categorical shifts between inset and high floodplains. Organic matter and nutrient content in floodplain soils increased with the time since restoration, which highlights the importance of recovery time after construction that is needed for restored systems to increase ecosystem functions. Our results highlight the importance of restoring floodplains downstream of sources of impairment and building them at lower elevations so they flood frequently, not just during bankfull events. This integrated approach has the greatest potential for increasing trapping of sediment, nutrients, and associated pollutants in restored streams and thereby improving water quality in urban watersheds.

1. Introduction

Billions of dollars are spent each year on river restoration in the U.S. to mitigate the negative impacts of urbanization and other anthropogenic stressors to aquatic ecosystems (Bernhardt et al., 2005; Bernhardt and Palmer, 2007). Many of these practices focus on channel stabilization and reducing bank erosion to provide a stable geomorphic template upon which multiple ecosystem services could then establish. This is challenging in urban watersheds where imperviousness and piped stormwater conveyance systems transport water to receiving streams quickly, resulting in high peak flows that can undermine the channel restoration (Paul and Meyer, 2001; Walsh et al., 2005a). The capacity for traditional restoration techniques (e.g., Natural Channel Design, NCD) to match the scale of the problem is questionable (Walsh et al., 2005b; Sudduth et al., 2007). Increasingly, approaches that reconnect streams with existing or newly constructed floodplains and near-stream wetlands are being implemented (Harrison et al., 2014; Wohl et al., 2015; Hester et al., 2016). These practices reduce peak flows in the main channel, which limits scour and erosion, while increasing retention time in floodplains for physical and biological processes to occur.

In urban headwater streams with space constrictions due to nearby infrastructure (e.g., buildings, roads), enhanced floodplain connectivity is often attempted through creation of a relatively narrow, shallow, and armored channel to convey baseflow and a near-stream, low-elevation inset floodplain that is typically 2–3 times channel width and frequently accessed during high flow (Doll et al., 2003). Channel designs vary and can include multiple levels of flat, inset floodplains with distinct transitions or have a consistent, shallow bank slope (e.g., 4:1) The inset floodplains created during restoration are inundated multiple times per

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year during storm events but hydrologic intensification in urban watersheds means that these small systems are not flooded for long periods of time (Craig et al., 2008; Roley et al., 2012). Engineered inset floodplains generally have dense herbaceous vegetation and high groundwater tables, providing labile carbon (C) and reducing conditions that promote nitrogen (N) removal via denitrification (Kaushal et al., 2008; Roley et al., 2012), and the dense vegetation enhances trapping of sediment and particulate phosphorus (P) (Kröger et al., 2013; Davis et al., 2015). Although less frequently accessed, higher elevation floodplain areas further from the stream have variable vegetation (e.g., managed turf grass, herbaceous grasses, deciduous trees) but can trap sediment and associated pollutants during large storm events (Hupp et al., 2013). Often higher floodplains are also constructed as part of the restoration project; however in some cases, the floodplain may pre-exist depending upon the stream and riparian zone condition. Despite the widespread implementation of stream-floodplain restoration to improve water quality, surprisingly little quantitative information on resulting nutrient and sediment retention rates and the factors that influence their variation is found in the literature, constraining the optimization of stream-floodplain restoration designs to maximize water quality benefits.

Sediment and nutrient trapping in natural and restored stream-floodplain systems is strongly linked to flood pulsing and hydrologic connectivity with the channel (Junk et al., 1989; Tockner et al., 1999). Biotic (e.g., vegetation, biogeochemical process rates) and hydrologic (e.g., residence times, flow paths) factors control rates of nutrient retention, removal and release. Herbaceous vegetation in the newly created floodplains increases surface roughness slowing stream water velocities and aiding in deposition of sediments that can have high concentrations of adsorbed NH_4^+, organic N, P and other contaminants (Surridge et al., 2012; Noe et al., 2013; Davis et al., 2015). Deposition of coarse-grained material is likely near the channel where velocities are higher and finer grained material with greater nutrient and organic content deposited further upslope (Hupp et al., 2013). High water tables and extended time of inundation in near-stream areas creates reducing conditions that favor redox dependent microbial processes, including N removal via denitrification (Heiler et al., 1995; Forshay and Stanley, 2005; Roley et al., 2012). Anoxic conditions allow for N removal via denitrification, however this may occur at the expense of P release (Loeb et al., 2008; Surridge et al., 2012). A different response may emerge in unrestored headwater urban floodplains where short residence times and lowered groundwater tables may limit redox dependent processes and high peak flows scour organic matter from floodplain surfaces rather than promote sedimentation (Groffman et al., 2003; Noe et al., 2013). Dry floodplain soils may also nitrify and leach nitrate back to the stream channel (Bechtold et al., 2003).

Variable hydrologic connectivity creates different functional geomorphic units laterally across floodplains that control moisture, organic matter content and vegetation and thereby influence rates of biogeochemical processes, including nutrient deposition, mineralization and denitrification (Noe et al., 2013). We use this framework to characterize the controls on nutrient dynamics in restored stream-floodplain ecosystems. We expect that the simplified channel geometry of restored floodplains in constrained urban stream corridors will result in three distinct geomorphic units, each with different hydrologic connectivity: (1) baseflow channel, (2) inset floodplain and (3) high floodplain. We anticipate that increased connectivity between streamwater and reconnected inset floodplains will lead to greater frequency of saturated conditions, increased nutrient inputs and deposition of coarse-grained sediment. Conversely, we expect to see less frequent flooding in the high floodplains but greater deposition of fine-grained sediments and organic matter.

We hypothesize that the net effect of greater hydrologic connectivity and resulting nutrient inputs to inset floodplains will enhance nutrient transformations compared to high floodplains. We also hypothesize that restoration age (i.e., the number of years since project

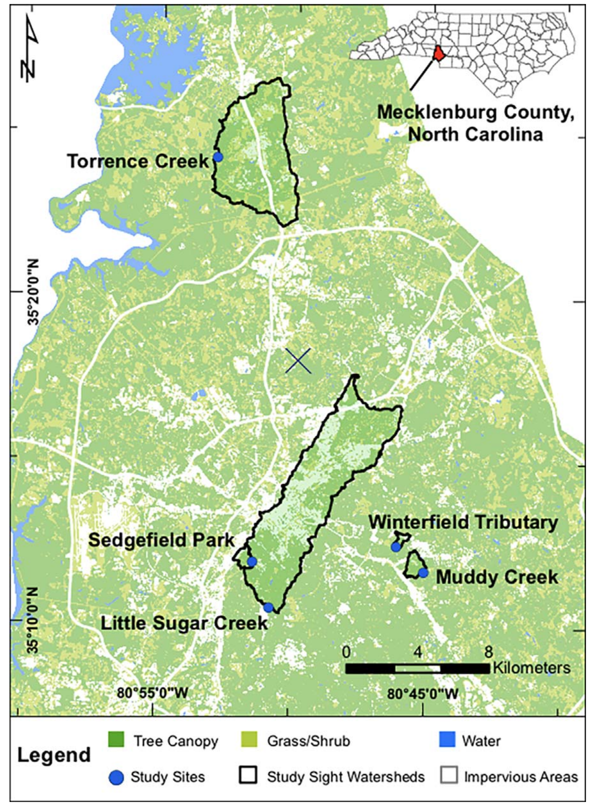

Fig. 1. Stream locations showing vegetated cover and watershed area draining to each site.

completion) will be an important control on nutrient transformations through development of soil organic and nutrient pools (Wolf et al., 2011; Mahl et al., 2015). To test these hypotheses and to inform the optimization of stream restoration design for improving water quality, our objectives were to (1) measure rates of sediment and nutrient loading to the inset and high floodplains in five restored urban streams with varying ages of restoration, (2) quantify nutrient transformation rates, including potential denitrification and in situ N and P mineralization, in the same floodplain soils and (3) identify geomorphic and physicochemical drivers of nutrient transformations and sedimentation rates.

2. Methods

2.1. Site descriptions

Five urban streams in Charlotte, North Carolina, which is in the Piedmont region of the Southeastern U.S., were selected for this study (Fig. 1, Table 1). All restoration projects were completed using the Natural Channel Design approach (NCD, Rosgen, 2007) and a summary of the project components are listed for each site. The inset and high floodplains for all of the sites in this study were constructed as part of the restoration process. Site selection was conducted in consultation with the Charlotte-Mecklenburg Storm Water Services and local stream restoration experts to select stream reaches to study that represented a range of restoration ages and degree of hydrologic connectivity.

Dairy Branch at Sedgefield Park (SP) was constructed in 2006 and flows through a municipal park. The watershed extends above the municipal park into commercial and residential districts (43.4% imperviousness, REF) with a drainage network of culverted and degraded (over-widened and deeply incised) and restored channels. The restored study reach includes a partial canopy of deciduous shrubs and trees as well as herbaceous grasses and sedges in the periodically mowed (no