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Estimating sediment and phosphorus loads from streambanks with and without riparian protection

Ronald B. Miller[a], Garey A. Fox[a,*,1], Chad J. Penn[b], Stuart Wilson[b], Abigail Parnell[a], Rebecca A. Purvis[a], Kelsey Criswell[a]

[a] Oklahoma State University, Biosystems and Agricultural Engineering, 120 Agricultural Hall, Stillwater, OK, United States of America
[b] Oklahoma State University, Department of Plant and Soil Sciences, 268 Agricultural Hall, Stillwater, OK, United States of America

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ABSTRACT

In some watersheds, the majority of the total sediment load to streams and rivers is from streambanks, but insufficient data exist on actual loading from this source and the potential protective effect of riparian protection in many watersheds. Using aerial imagery, video reconnaissance for unstable banks, and streambank phosphorus (P) sampling, this research studied streambanks throughout the Barren Fork Creek (BFC) watershed within Oklahoma to address four major objectives: (i) quantify the amount of streambank erosion and failure throughout the watershed, (ii) quantify the magnitude and the intra-site and inter-site spatial variability in streambank soil chemistry, water soluble phosphorus (WSP), and total phosphorus (TP), (iii) quantify the load of WSP and TP from streambanks in the watershed, and (iv) estimate the benefit of riparian management practices. Ten streambank study sites were selected on BFC, including seven sites with existing or historic riparian forest (historically protected, HP), and three with no riparian forest (historically unprotected, HUP). Median and mean streambank migration rates were 9.5 and 17.5 m for the HP sites compared to 37.6 and 49.2 m for the three HUP sites over the seven year period. Total WSP from streambanks on BFC from unprotected and failing banks was approximately 1.2×10^3 kg yr^{-1}, which represented approximately 10% of the dissolved P load estimated from USGS gauges on BFC. The estimated TP load was approximately 9.0×10^4 kg TP yr^{-1}, which exceeded the TP load estimated from gauge data, although TP is largely sediment-bound and thus subject to sediment transport dynamics such as floodplain deposition. Streambanks represented a considerable source of P, and riparian forest sites showed significantly lower rates of retreat. The methodology of using detailed P characterization, lateral retreat rates from aerial photography, and video reconnaissance to characterize bank stability was an effective approach for assessing the WSP and TP load contribution from streambanks.

1. Introduction

Nutrients and excess sediment are two of the primary pollutants of surface waters. Nitrogen is a concern, but phosphorus (P) is generally considered the limiting nutrient in most surface water systems (Daniel et al., 1998). Main sources of P include fertilizer, legacy sources of P from discharges in the upper portion of the watershed, and wastewater treatment plant discharge. An excess of nutrients, primarily the limiting nutrient P (Schindler et al., 1971), in streams and lakes can lead to eutrophication which, in turn, decrease their quality and productivity (Heeren et al., 2011). However, there are currently insufficient data in many watersheds to determine the loading of sediment and P from streambanks (Fox and Wilson, 2010).

Bank erosion has been recognized as a source of P to receiving waters in some studies, with estimates ranging from 7 to 10% of annual total phosphorus (TP) in Minnesota (Sekely et al., 2002) and 14 to 24% of TP in Denmark (Laubel et al., 2003). Zaimes et al. (2008) found that P concentrations within streambank soils in Iowa was fairly constant, but that streambank erosion, and hence sediment and P loading, varied with riparian land use. Kronvang et al. (2012) examined both erosion and deposition within plots of erosion pins

* Corresponding author. Tel.: +1 405 744 8423; fax: +1 405 744 6059.
E-mail addresses: ron.miller@okstate.edu (R.B. Miller), garey.fox@okstate.edu (G.A. Fox), chad.penn@okstate.edu (C.J. Penn), stuart.wilson@okstate.edu (S. Wilson), abigail.parnell@okstate.edu (A. Parnell), rebecca.purvis@okstate.edu (R.A. Purvis), kelsey.criswell@okstate.edu (K. Criswell).
[1] Professor and Orville L. and Helen L. Buchanan Endowed Chair.

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and were able to estimate net P movement. They determined that bank erosion was a significant source of P that accounted for 21–62% of annual loads for a Danish stream with cohesive banks. Bank erosion was significantly lower along reaches with trees and shrubs compared to reaches dominated by grasses. Those studies documented erosion rates on the order of tens to several hundreds of millimeters per year (mm yr^{-1}) using measurements from erosion pins (Sekely et al., 2002; Laubel et al., 2003; Zaimes et al., 2008). Studies are needed that focus on P loading from higher magnitudes of bank erosion.

Billions of dollars have been spent on streambank stabilization to help slow bank retreat and reduce sediment loading (Lavendel, 2002; Bernhardt et al., 2005), and those riparian vegetated-based protections can drastically reduce streambank erosion in locations. However, estimates of actual decreases in sediment and P are limited beyond the studies mentioned previously (Sekely et al., 2002; Laubel et al., 2003; Zaimes et al., 2008). Additional research is needed on streambank contributions to P loading and especially to document the following: (i) intra-site and inter-site spatial variability in streambank soil chemistry, water soluble phosphorus (WSP), and TP to determine the necessity of detailed sampling for WSP and TP from streambanks throughout watersheds and (ii) estimate the benefit of riparian protection practices in reducing sediment and WSP/TP loads in watersheds.

One such area of concern related to sediment and P is eastern Oklahoma and western Arkansas (White et al., 2009, 2010; Andrews et al., 2009) where poultry production is a regional industry. After export of poultry products, what remains in the region is nutrient rich poultry litter, which is bulky, expensive to export, and therefore is often applied to nearby pastures, including those in floodplains, as an inexpensive fertilizer. Historic litter application rates were based on plant nitrogen requirements, which over time can result in P accumulations in the soil since litter is enriched relative to P. Sharpley et al. (2003) noted that feed imported to support concentrated poultry production has resulted in a net increase of nutrients in the region. As a result, many soils within poultry-dense watersheds possess soil P concentrations beyond both the need of plants and at levels that could allow the soil to act as a P source to surface waters. Streams and water bodies in the eastern Oklahoma Ozarks are very sensitive to nutrient pollution, so determining load sources for the waterways is important. However, bank erosion as a P-load source has often been ignored (Heeren et al., 2012), even though Harmel (1997) and Harmel et al. (1999a) estimated that 3.5 million tons of sediment (or 1.05 kg ha^{-1} on an areal basis) entered the river between 1979 and 1991 as a result of bank erosion in the Illinois River.

Most streambanks in the Oklahoma Ozarks are composed of layers with contrasting textures, commonly sandy- or silt-loam topsoil over a coarse gravel subsoil, which are labeled "composite banks" in the literature (Thorne and Tovey, 1981). These banks exhibit distinct erosional characteristics that can lead to episodes of rapid stream migration. Erosion typically occurs in a sequence beginning when fluvial entrainment of the underlying, unconsolidated gravel produces an undercut bank, which eventually fails when the weight of the unsupported block exceeds the cohesive strength of the soil (Heeren et al., 2012; Midgley et al., 2012). Erosion rates for these composite banks can range to tens of meters per year (m yr^{-1}) or more, and in cases can reach this magnitude in a single runoff event. Harmel et al. (1999a,b) reported short-term erosion rates of up to 8.1 m yr^{-1} and long-term rates up to 6.5 m yr^{-1} on the Illinois River in the Oklahoma Ozarks.

It is known that riparian vegetation can affect bank stability, and it is commonly assumed that the strength of plant roots anchored in the banks add some amount of strength to the soil which increases its resistance to mass failure, a force component termed "root cohesion" (c_r) (Cancienne et al., 2008; Pollen-Bankhead and Simon, 2009). Trees, shrubs and grasses all have roots and thus all presumably contribute to c_r. However, trees have a much larger range of root sizes and tensile strengths, all of which persist throughout the seasonal progression each year. Also the presence and absence of trees provides a large visual contrast that can be easily determined through aerial imagery. It has been observed in the composite banks of the Ozark region that that the bulk of tree root mass exists in the upper cohesive soil layer only. Therefore, it is likely that in composite banks, tree roots only provide additional geotechnical strength to the upper cohesive topsoil and not to the unconsolidated gravel. Given the mechanism of bank retreat in composite bank systems, it is important to understand the effects of c_r and riparian protection on composite bank retreat, and hence on sediment and P loading from those banks to streams. This knowledge can justify the use and demonstrate the effectiveness of conservation practices such as the installation of riparian buffers or vegetative filter strips (Sabbagh et al., 2009; Poletika et al., 2009; Fox and Penn, 2013).

Therefore, within the larger context of assessing the importance of bank erosion as a source of P loading in an Oklahoma Ozark watershed, the objectives of this research included the following: (i) quantify the amount of streambank erosion and failure, (ii) quantify the magnitude and the intra-site and inter-site spatial variability in streambank soil chemistry, WSP, and TP, (iii) quantify the potential load of WSP and TP from streambanks in the watershed, and (iv) estimate the benefit of riparian management practices in composite bank systems.

2. Materials and methods

2.1. Description of the watershed

Barren Fork Creek (BFC) is a fourth order stream, originating in northwestern Arkansas which flows west through the Boston Mountains and Ozark Highlands ecoregions, and reaches its confluence with the Illinois River at Lake Tenkiller near Tahlequah, OK (Fig. 1). The BFC watershed is within the Illinois River watershed, which has many areas listed on the 303(d) list for nutrient related impairments. The BFC has a natural meander and high degree of sinuosity, but changes in land use in the past 150 years may have resulted in accelerated rates of streambank erosion and lateral channel migration (Jacobson and Primm, 1997; Jacobson and Pugh, 1998; Heeren et al., 2012). This watershed, which is typical of those in the Ozark ecoregion in eastern Oklahoma, is characterized by cherty soils and gravel bed streams (Fuchs et al., 2009; Fox et al., 2011).

Streambanks within the watershed commonly are composite banks (Fig. 2, Midgley et al., 2012). The top layer is typically a cohesive silt loam soil which can range in thickness from several centimeters to more than a meter. Underlying the topsoil, separated by a very sharp change in texture, is typically a non-cohesive "imbricated" gravel layer, similar in size to the streambed gravel, which also ranges in thickness from tens of centimeters to a meter or more. Also typically present is a gravel "toe" consisting of loose larger gravel particles detached from the imbricated gravel but not yet transported away. Previous research experience within the watershed has shown that the gravel extends downward to the bedrock which can be 10 m or more below the ground surface. Studies on BFC sites by Fox et al. (2011), Mittelstet et al. (2011), Heeren et al. (2012), and Midgley et al. (2012) noted the occurrence of episodic events of dramatic bank retreat (i.e., 7.8–20.9 m of bank retreat during the summer of 2009 over a 100 m reach).

2.2. Study sites

Ten streambank study sites were selected at locations along BFC in Oklahoma, which were designated by letters A–J (Fig. 1,