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Phosphorus algal availability and release potential in suspended and streambed sediments in relation to sediment and catchment characteristics

Jingjun Su[a], Eric van Bochove[b,*], Jean-Christian Auclair[c], Georges Thériault[d], Jean-Thomas Denault[d], Catherine Bossé[d], Xuyong Li[a], Chengxiao Hu[e]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China
[b] Science and Technology Branch, AAFC, 2828 Laurier Blvd, Room 640, Québec, QC G1V 0B9, Canada
[c] Institut national de la recherche scientifique, Centre Eau, Terre et Environnement, Quebec, Canada
[d] Soils and Crops Research and Development Centre, Agriculture and Agri-Food Canada, Quebec, Canada
[e] Micro-Elements Research Center, College of Resources and Environment, Huazhong Agricultural University, Wuhan, China

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ABSTRACT

Both suspended and streambed sediments from two pairs of streams (intervention outlet and control outlet, and Branch 14 and Branch 15) in livestock intensive catchments were analyzed for total phosphorus (TP), algal available P (AAP), P fractions and P saturation index (PSI). The variations in sediment P characteristics associated with sediment type and study sites were investigated; and the key variables controlling the variations were explored. Relative to streambed sediments, suspended sediments had significantly higher storage of TP and AAP and greater potential to continue adsorbing P from the water column. The differences between the two groups of sediments mainly resulted from differences in sediment particle size. For both suspended and streambed sediments, concentrations of TP, AAP, organic P (Po) and inorganic P (Pi) were not significantly different between the two catchment outlets, but were significantly higher in Branch 15 than in Branch 14; PSI values were considerably higher in the control outlet than at any of the study sites within the intervention micro-catchment. Sediment properties (e.g., calcium (Ca), aluminum (Al) and organic matter (OM)) and catchment characteristics (e.g., soil M3P status and drainage area) explained 62–87% of the variations in log-transformed TP, AAP, Po, Pi and PSI in suspended sediments, with sediment properties being the main contributor. For streambed sediments, variations in P concentrations and PSI were less well explained (13–56%), and sediment OM was the most importance predictor. Forest area percentage in landscape explained limited (3%) proportion of the variations in streambed sediment P concentrations and PSI.

1. Introduction

Elevated phosphorus (P) could accelerate the eutrophication in fresh waters (Conley et al., 2009). Sediment-associated P loss from agricultural land has been identified as an important source of non-point P in receiving freshwaters (USEPA, 2002). The sediment P will either be deposited and stored temporarily on the streambed, or will be flushed out of the catchment as suspended load (Holtan et al., 1988; Jarvie et al., 2005). Much has been known about the total loads of sediment and P transferred from land to water in various scales (plot, field, catchment, etc.) (Sharpley et al., 1999; McDowell et al., 2001; Steegen et al., 2001; Panuska et al., 2008), but little is known about if the sediments would retain P from or release P to the water column and to what extent they could release algal available P after entering the receiving waters.

Several researches recommended using the combined algal availability and P saturation index (PSI) tests to predict the potential for sediments to retain from or release P to the water column (Nguyen and Sukias, 2002; Haggard et al., 2007; Palmer-Felgate et al., 2009). The algal availability of sediment P could be assessed by a single chemical extraction by 0.1 M NaOH (Dorich et al., 1985), or by a sequential chemical extraction (Boström et al., 1988b).

* Corresponding author. Tel.: +1 418 648 3316; fax: +1 418 648 7342.
E-mail addresses: jjsu@rcees.ac.cn (J. Su), eric.vanbochove@agr.gc.ca (E. van Bochove), jean-christian.auclair@ete.inrs.ca (J.-C. Auclair), Georges.Theriault@agr.gc.ca (G. Thériault), Jean-Thomas.Denault@mddep.gouv.qc.ca (J.-T. Denault), catherine.bosse@agr.gc.ca (C. Bossé), xyli@rcees.ac.cn (X. Li), hucx@mail.hzau.edu.cn (C. Hu).

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The P fractionation separates sediment P into operational fractions with different algal availabilities, varying from readily available exchangeable P and reducible P, to less available aluminum P (Al-P) and organic P, to more recalcitrant calcium (Ca) and apatite P and residual P (Psenner et al., 1988; Hupfer et al., 1995; Rydin, 2000). PSI describes the portion of the sediment binding sites already occupied with P (Sallade and Sims, 1997b; Beauchemin and Simard, 1999). Critical threshold values of PSI, above which the sediment P is likely to be released, have been established to assess the vulnerability of sediment P sorption to overlying water (Sallade and Sims, 1997a).

Essentially, the algal availability and release potential of sediment P is controlled by the sediment composition (e.g., metals oxides or hydroxides, clay minerals, organic matter (OM)) which determines the magnitude of P retention and the pattern of P fractionation (Holtan et al., 1988; Reddy et al., 1999; Evans et al., 2004; van der Perk et al., 2007), and the sediment particle size which influences the sediment composition (Palmer-Felgate et al., 2009; Kerr et al., 2011). The conditions at the sediment–water interface (e.g., pH, Eh, temperature, P concentration gradient) would determine when and how algal available P would be mobilized and released (Boström et al., 1988a,b). The physicochemical drivers for sediment P algal availability and release potential have been extensively studied at the at the sediment–water interfaces (Boström et al., 1988a; Hupfer et al., 1995; Perkins and Underwood, 2001; Pant and Reddy, 2003; Søndergaard et al., 2003). But limited studies have linked this aquatic sediment P with the terrestrial sources of P (Haygarth, 2005; Kerr et al., 2011) to explore the landscape drivers of sediment P contents and forms.

Nowadays, the effective management of non-point source P requires a whole of catchment approach (Kerr et al., 2011). Understanding the relations between terrestrial and sediment P would be essential to identify the controls governing the sediment P algal availability and release potential at catchment scale and assist the development of P mitigation strategies. A few recent studies have attempted to address the impacts of catchment characteristics, such as land use (Palmer-Felgate et al., 2009; Amiri et al., 2012), underlying geology (Ballantine et al., 2008, 2009), soil P status (van der Perk et al., 2007; Rawlins, 2011) and flow conditions (Ellison and Brett, 2006) on the contents of either suspended or streambed sediment P. Taking land use as an example, TP or exchangeable P contents in stream sediments generally increase with the proportion of agricultural land use within a catchment or drainage area, while a decrease is observed as the proportion of forested area increases (Smith et al., 2005; SanClements et al., 2009; Amiri et al., 2012). However, impacts of these factors on sediment P were generally qualitative and to what extent these factors would impact sediment P is rarely reported. No studies to date have quantified the impacts of various factors from landscape and sediment themselves on sediment P algal availability and release potential at catchment scales. Therefore the primary aim of this study was to investigate the P algal availability and release potential in both suspended and streambed sediments and to identify the role sediments played in the studied streams. The second aim was to investigate the between and/or within micro-catchment variations in P characteristics of both sediments, to identify the catchment and sediment characteristics controlling any spatial patterns found, and to quantify their relative contributions.

2. Materials and methods

2.1. The study micro-catchments

The study took place in the Bras d'Henri River catchment, which is highly impacted by intensive farming and is part of the national project of watershed evaluation of beneficial management practices (BMPs) of Agriculture and Agri-Food Canada (WEBs program). Two micro-catchments of the Bras d'Henri River Catchment (167 km^2), named "intervention" (236 ha) and "control" (423 ha) were located south of Quebec City, Canada (Fig. 1). Best Management Practices (BMPs) including surface runoff control (e.g., riparian buffer strips, grassed waterways), crop rotation and slurry application method improvement were implemented in the intervention micro-catchment but not in the control micro-catchment. The main objective of these BMPs was to reduce soil erosion and nutrient loss loads. Soil erosion and surface runoff control BMPs were implemented and completed in 2007. Crop rotation and slurry application method improvement BMPs, which mainly targeted N loss and odor, had been implemented since 2004 and 2005, respectively. Since all sampling activities, described below, have taken place from June 2008 to December 2009 after the last BMP was implemented in early 2007 and since that there had yet been no measurable effect of these implemented BMPs on water quality when this study was undertaken, their impact on sediment P algal availability and release potential are not discussed in this paper.

The regional climate is characterized by long cold winters and short mild summers, with the average annual precipitation and temperature respectively being 1126 mm and 4.3 °C. The two micro-catchments are typical agricultural regions characterized by perennial forage crop and intensive annual crop (corn and soybean) production (Table 1), coupled with a high animal density of 5.7 animal unit ha^{-1} (hogs 59%, and cattle 23%). Land use map based on the field survey in 2007 indicates that the intervention micro-catchment is mainly covered by annual crops (61%), forage crops (21%) and forest (12%), while in the control micro-catchment, the main land uses are forage crops (49%), annual crops (26%) and forest (16%) (Table 1). A detailed soil survey in Bras d'henri River catchment indicates that soils are mainly silt loams in the control micro-catchment and sandy loams in the intervention micro-catchment, and that the intervention micro-catchment has equal amounts of podzolic and gleysolic soils (50%), whereas gleysols are predominant (72%) in the control micro-catchment (Lamontagne et al., 2009) (Table 1).

Two major streams located within the intervention micro-catchment, Branch 14 and Branch 15, were also selected to investigate the 'within catchment' variation in sediment P characteristics (Fig. 1). Branch 14 and Branch 15 respectively drain 126 ha and 80 ha of area. Land use in Branch 14 is mainly cropland (61%) with the remaining land covered with forest (22%) and forage (15%). Land use in Branch 15 is split between cropland (70%) and forage (25%) (Table 1). Podzols and gleysols cover 48% and 39% respectively of the drainage area of Branch 14, and 55% and 30% of Branch 15 (Table 1).

Soil P concentrations were obtained from a soil fertility survey conducted in the studied micro-catchments by the Club de fertilization de la Beauce (CFB) in 2007 and 2008. Agricultural land including crop and forage lands in each micro-catchment were divided into fields varying in size ($\leq$10 ha) and presenting uniform land use and topography. A composite sample was made from 15 soil sub-samples randomly taken at a 15–17 cm depth across each field. In total 68, 77, 27 and 35 soil samples were respectively collected from the intervention micro-catchment, the control micro-catchment, Branch 14 drainage area and Branch 15 drainage for Mehlich-3 P (M3P) analysis (Mehlich, 1984). M3P test has been used as an "agri-environmental soil test" in USA and eastern Canada (Khiari et al., 2000; Sims et al., 2002). No soil M3P concentrations in forest of studied micro-catchments were measured, but these would be expected to be lower than in the Ap horizons of agricultural fields as they do not receive any manures nor fertilizers in these micro-catchments (personal communication,