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Field-derived phosphorus accumulation rates and fractionation in bioretention cells

Taux d'accumulation et fractionation du phosphore sur le terrain dans un système de biorétention

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RÉSUMÉ

Dans cette étude, nous avons évalué les procédés qui contrôlent le devenir du phosphore (P) dans les systèmes de biorétention. D'abord, nous avons estimé les taux d'accumulation du P à partir d'échantillons de terrains collectés sur 9 ans à deux profondeurs d'un système de biorétention. Ensuite, nous avons conduit des extractions séquentielles du sol pour caractériser les fractions du P dans des échantillons distribués horizontalement et verticalement dans le système de biorétention. Les taux d'accumulation étaient plus élevés en surface qu'en profondeur et étaient entre 4 et 80 mgP kg⁻¹ yr⁻¹. L'accumulation du P dans le sol était linéaire avec le temps sur les 9 années de l'étude, suggérant que ce système de biorétention n'était pas encore saturé en P. Les extractions séquentielles ont permis d'associer le P avec 6 fractions principales d'origine organique et inorganique. Cette analyse a montré que le P associé aux espèces sensibles au potentiel d'oxido-réduction et le P associé à la matière organique étaient les deux fractions qui représentaient le mieux la variation du P dans le système.

ABSTRACT

In this study, we evaluated the processes affecting phosphorus (P) in bioretention cells. First, we estimated the accumulation rates of P using field samples collected over 9 years at two depths of a bioretention cell. Second, we conducted sequential soil extractions to investigate the fractions of P in vertically- and longitudinally-distributed samples. The accumulation rates were higher at the top than in the core of the bioretention media and ranged from 4 to 80 mgP kg⁻¹ yr⁻¹. The accumulation trends were linear with time, thus indicating that the bioretention cell was not saturated with P yet. The sequential extractions allowed to associate P with 6 main fractions of organic or inorganic origins. This analysis showed that redox-sensitive P and organic matter-associated P (organic P, humic-bound P, and exchangeable P) fractions best represented total P variation in the system.

KEYWORDS

Phosphorus, Bioretention cells, Green infrastructure, Stormwater runoff, Accumulation Rates

1 INTRODUCTION

Bioretention cells are a popular type of green infrastructure for urban stormwater management. They show promising performance in managing stormwater and mitigating a multitude of pollutants. In urban catchments, they reduce the 'flashiness' and overall volume of flows resulting from storm events by promoting storage, groundwater infiltration, and evapotranspiration. Previous studies have shown highly variable phosphorous (P) removal in bioretention cells. There is therefore a need for more comprehensive understanding of P biogeochemistry within bioretention systems to identify the processes responsible for such variations.

The goals of this study are to characterize the chemistry of P in bioretention cells and estimate P accumulation rates from field-collected bioretention media.

2 MATERIALS AND METHODS

2.1 Site description

We studied a 6-cell bioretention system installed in 2012 in Mississauga, ON, Canada. The catchment area is 6,456 m² and approximately 50% impervious. The cells are approximately 14.7 m × 1.6 m each, initially designed with layers of 5-7 cm deep mulch, 45 cm filter media (consisting of 85-88% sand and 8-12% fines with 3-5% organic content by weight) and 15 cm sand. The cells are interconnected by an underdrain.

2.2 Sampling and analysis

Soil samples were collected in years 1 (2013), 2 (2014), 4 (2016), 7 (2019) and 9 (2021) after construction at various longitudinal and vertical locations in the cells. The soil samples were frozen to -20°C for three days, freeze dried, homogenized, ground with a mortar and pestle, sieved to 125 µm and stored in a desiccator before analysis. All samples were analyzed for total phosphorus (TP). A subset of the samples was analyzed for P fractions using a sequential extraction (SEDEX) method following published methods (Baldwin, 1996; Ruttenberg, 1992; Ruttenberg et al., 2009). The fractions were referred to as: 1) exchangeable P, 2) humic acid-bound P, 3) iron-bound P, 4) carbonate and calcium-bound P, 5) mineral-bound P of detrital origin, and 6) organic residual-bound P. Finally, some samples were also analyzed for total carbon (TC), total organic carbon (TOC), total nitrogen (TN), total organic nitrogen (TON), and common metals.

3 RESULTS AND DISCUSSION

3.1 Total phosphorus and other soil chemistry parameters

The soil TP concentrations increased linearly over time in the bioretention cells. This suggests that this bioretention system did not reach P saturation yet, even after 9 years of operation. The accumulation rates near the surface (~ 70 to 80 mgP kg⁻¹ yr⁻¹) were twice as large as those estimated in deeper soil horizons (~ 4 to 40 mgP kg⁻¹ yr⁻¹). These field-based P accumulation rates are comparable to those of Johnson and Hunt (2016) at 15 mgP kg⁻¹ yr⁻¹ over 11 years and Johnson and Hunt (2019) at 9 mgP kg⁻¹ yr⁻¹ over 17 years. These field-estimated P accumulation rates are critical to predict the lifetime of bioretention cells for P retention.

There was insignificant TN and TON in the soil. The TP concentrations decreased with depths in all cells except in the last one (i.e., Cell #6). Cell #6 was the most downstream cell. It had significantly higher TP concentrations in our samples than in the other cells. It also had the highest soil P accumulation rates. Three potential contributing factors to this were: its location on the corner of two streets (rather than just one), the reception of a greater proportion of runoff due to its position, and an upward flow from upstream cells. While the first two factors are common to many bioretention system designs, the interconnection of multiple cells through a linked underdrain rather than surface level connections is an uncommon design feature of our site. The subsurface peak in TP observed in Cell #6 could potentially be explained as evidence of deposition during backwashing of effluent from upstream cells within the system during

high-intensity events.

3.2 Phosphorus fractionation

As observed for TP concentrations, the TOC concentration was the highest at the top and decreased rapidly with depth. Soil samples closer to the surface were proportionally higher in more labile, organic-related P fractions (i.e., exchangeable P, humic-bound P, and residual/organic P fractions) than those deeper in the core. In contrast, mineral-bound P fractions, particularly the calcium-related, tightly-bound, P fractions associated with detrital calcium minerals and authigenic apatite adsorption/precipitation minerals did not exhibit a clear relationship with sample depth. However, absolute concentrations of P in these fractions remained relatively stable and the proportional shift was primarily driven by a decrease in the other fractions as depth increased. We also observed a reduction in the concentrations of redox-sensitive Fe-associated P in the deepest samples analyzed. This fraction otherwise remained relatively constant in proportion throughout the rest of the soil profile.

4 CONCLUSIONS

Our study provided direct evidence and quantities of TP accumulation in bioretention cells. All six P fractions were present in significant quantities and showed spatially heterogeneous distribution patterns providing evidence for complex P behavior within the system. Our findings also suggest that the distributions are likely to also change over time in addition to the horizontal and vertical variabilities we observed. Future research should explore the factors affecting fractional P composition in bioretention systems as a result of changing environmental conditions and increasing age.

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