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Bioretention cells under cold climate conditions: Effects of freezing and thawing on water infiltration, soil structure, and nutrient removal

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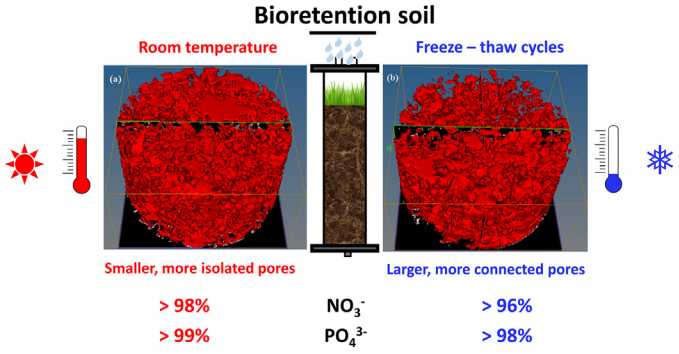
HIGHLIGHTS

- Effects of freeze-thaw cycles (FTCs) on bioretention performance were assessed.
- Column experiments were conducted with soil from an active bioretention cell.
- FTCs resulted in larger pores and more small pores maintaining high infiltration.
- Very high nitrate and phosphate removal was observed in the soil columns.
- With proper design, bioretention cells are efficient under cold winter conditions.

GRAPHICAL ABSTRACT



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ABSTRACT

Bioretention cells are a popular control strategy for stormwater volume and quality, but their efficiency for water infiltration and nutrient removal under cold climate conditions has been poorly studied. In this work, soil cores were collected from an active bioretention cell containing engineered soil material amended with a phosphate sorbent medium. The cores were used in laboratory column experiments conducted to obtain a detailed characterization of the soil's bioretention performance during six consecutive freeze–thaw cycles (FTCs, from −10 to +10 °C). At the start of each FTC, the experimental column undergoing the FTCs and a control column kept at room temperature were supplied with a solution containing 25 mg/L of bromide, nitrate and phosphate. Water saturated conditions were established to mimic the presence of an internal water storage zone to support anaerobic nitrate removal. At the end of each FTC, the pore solution was allowed to drain from the columns. The results indicate that the FTCs enhanced the infiltration efficiency of the soil: with each successive cycle the drainage rate increased in the experimental column. Freezing and thawing also increased the saturated hydraulic conductivity of the bioretention soil. X-ray tomography imaging identified a key role of macro-pore formation in maintaining high infiltration rates. Both aqueous nitrate and phosphate supplied to the columns were nearly completely removed from solution. Sufficiently long retention times and the presence of the internal water storage zone promoted anaerobic nitrate elimination despite the low temperatures. Dissolved phosphate was efficiently trapped at all depths in the soil columns, with ≤2% of the added stormwater phosphate recovered in the drainage effluent.

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These findings imply that, when designed properly, bioretention cells can support high infiltration rates and mitigate nutrient pollution in cold climates.

1. Introduction

Bioretention cells are urban stormwater control systems made of a depression in the ground, typically covered by mulch and a wide range of plants, and where the original soil has been replaced by an engineered medium designed to enhance water infiltration and promote contaminant removal. Bioretention cell efficiency for nutrient removal and water infiltration has been extensively studied under temperate climate conditions (Hunt et al., 2012; Roy-Poirier et al., 2010). Even though nitrogen and phosphorus removal rates are often strongly variable, specific design strategies have proven effective at limiting nutrient export out of the system. For example, the implementation of a saturated internal water storage zone can be used to support denitrification (Dietz and Clausen, 2006; Kim et al., 2003), and various engineered media amendments, such as fly-ash, water treatment residual, red mud, and alum can be added to promote sustainable phosphorus adsorption (Lucas and Greenway, 2011; O'Neill and Davis, 2012; Yan et al., 2016; Zhang et al., 2008). Conversely, the performance of bioretention cells is not well known. Freezing and thawing cycles (FTCs) in particular are known to affect natural soil structure by destabilizing soil aggregates, in particular for soils with high water contents. The relocation of destabilized aggregates can clog some of the soil pores and reduce the infiltration capacity (Hayashi, 2013). Moreover, FTCs typically affect microbial activity and diversity and therefore the speciation and mobility of various chemical elements (Campbell et al., 2005; Matzner and Borken, 2008). Even though lower temperatures result in slower microbial activity, the breaking of soil aggregates and mortality of microorganisms and plant roots during FTCs produce readily bioavailable organic carbon that support denitrification upon thawing (Christensen and Christensen, 1991).

Engineered soil media used in bioretention cells have a high sand content in order to maintain high hydraulic conductivity. For example, in southern Ontario, bioretention media are recommended to consist of 85–88% sand (0.050–2.0 mm), 8–12% fines (<0.050 mm), and 3–5% organic matter, and to support infiltration rates >25 mm/h (Dhalla and Zimmer, 2010). In such sandy soil media, the effects of freezing and thawing on soil structure and nutrient removal are unclear due to a lack of research on the topic. For countries where winter temperatures are frequently below freezing, a better characterization of FTC effects on bioretention performance is critical to guarantee their functioning throughout the year, especially during early winter and early spring when repeated soil freezing and thawing is a common occurrence.

To date, some studies have described the performance of bioretention cells under cold temperate climate conditions, but for soil temperature >0 °C (e.g., Blecken et al. (2010), Khan et al. (2012a, 2012b)). However, many research gaps still exist (Kratky et al., 2017). In particular, very limited research has incorporated experimental conditions leading to successive freezing (soil surface temperature < 0 °C) and thawing (soil surface temperature > 0 °C) of bioretention soils (Al-Houri et al., 2009; Denich et al., 2013; Géhéniau et al., 2015; Moghadas et al., 2016; Muthanna et al., 2007; Muthanna et al., 2008; Valtanen et al., 2017). Several authors reported reduced infiltration rates during the freezing period due to a reduction in pore availability (Al-Houri et al., 2009; Muthanna et al., 2008), and increased infiltration rates upon thawing (Denich et al., 2013; Moghadas et al., 2016; Valtanen et al., 2017). However, the latter results are mostly of a descriptive nature, with no definitive explanation of the observations. Mechanism-oriented research is needed to characterize hydrological and contaminant transfer and transformation processes in bioretention cells undergoing freezing and thawing cycles (Kratky et al., 2017).

The methodologies used in soil FTC experiments have taken many forms, which makes it difficult to compare results among various experiments and relate them to real field conditions (Henry, 2007). Frost depths are usually limited to the top few centimetres of the soil due to the temperature buffering effect of snow cover, soil, mulch, and vegetation (Henry, 2007). Indeed, sub-zero air temperatures do not necessarily translate into sub-zero temperatures across the soil profile (Fach et al., 2011). A review by Henry, 2007 reported that soils rarely freeze below 5 cm in depth, even though deeper frost depths, up to 20 cm have been observed both in natural (Henry (2007) and references therein) and bioretention soils (Géhéniau et al., 2015; Roseen et al., 2009; Valtanen et al., 2017). Occasionally, in some areas of the world such as in west Canada, frost depths are highly variable and can go down to −45 cm (Christensen et al., 2013; He et al., 2015). The number, frequency, and amplitude of FTCs, as well as the target freezing temperature and the rate at which this temperature is first reached can have irreversible negative impacts on soil microorganisms and result in larger than expected effects on parameters and processes, such as soil structure and nutrient fate and transport (Henry, 2007).

In the present study, an experimental soil column set-up was used to freeze/thaw the top 5 cm in an undisturbed soil core collected from an active bioretention cell in a cold climate region. By imposing successive cycles of freezing and thawing on the bioretention soil column, the objectives of this study were to (1) characterize changes in bioretention infiltration capacity and soil structure, and (2) quantify the retention efficiencies of aqueous nitrate (NO_3^-) and phosphate (PO_4^{3-}) supplied at the top of the columns. In order to relate the observations to the FTCs, a control experiment with a column containing the same soil, but maintained at a constant room temperature, was also carried out.

2. Materials and methods

2.1. Bioretention cell site and sample collection

Soil samples were collected in September 2015 from a bioretention cell located in Ajax, Ontario, Canada and installed between October and November 2014 (Appendix A: Supplemental Material (SM) Fig. S1). The site is located in an urban catchment with a contributing 95% impervious area and receives runoff from a 4160-m^2 drainage area. The bioretention cell surface area is 488 m^2 and the depth of the engineered soil medium is 50 cm. The soil had mulch at the top and, prior to installation, was amended with a medium enriched in iron and aluminum oxides (Sorbtive® media, Imbrium Systems), in a proportion of 3.1% by volume, for enhanced phosphorus removal. Four undisturbed soil cores of 7.5 cm inner diameter and 45 cm length were sampled by manually pushing into the soil a custom-made coring tube, fitted with a top cap to hold the soil in place upon retrieval. The soil cores were taken approximately 5 cm apart from each other to ensure the columns had comparable grain size distributions and received similar stormwater runoff loadings. No rooted vegetation was present where the samples were collected and >50% of the bioretention surface had no plants and only mulch on top of the soil. The soil samples were immediately transported to the laboratory for the experiments.

2.2. Experimental setup

Three of the soil cores were used. They were inserted into the columns from the bottom by a custom-made lifting jack device that