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Soil texture and water retention as spatial predictors of denitrification in urban wetlands

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A B S T R A C T

Urban wetlands potentially play an important role in nitrate (NO_3^-) removal from stormwater, but nitrogen loading from the atmosphere and surface water must intersect with soil properties optimal for NO_3^- removal for this potential to be realized. We examined predictors of NO_3^- removal via the microbial process of denitrification in an urban wetland system in New Jersey, USA with highly heterogeneous soils. Soil cores representing the wide range of soil textures at the site were collected to examine relationships between intact core denitrification rates, denitrification enzyme activity (DEA), available inorganic nitrogen, and soil water retention characteristics. Water retention curves were characterized for pressure potentials ranging from −1 to −5000 cm and used to estimate pore size distribution parameters. The highest intact core denitrification rates occurred in soils located at low elevations, with high macroporosity, and low variability in soil pore radius. High DEA corresponded with high available soil NO_3^- and high elevation. Soil samples collected at 118 points from the site and analyzed for soil organic matter and texture fractions were used to create interpolated raster layers of properties related to high denitrification rates ("hot spots"). Weighted estimations of whole-site NO_3^- removal based on denitrification hot spots were higher than site estimations based on average denitrification rates, suggesting that studies using the latter approach may be underestimating NO_3^- removal at the landscape level. Stormwater channels at the site intersected with denitrification hot spots over 20% of total channel area, indicating that soils may be at least partially reducing total NO_3^- loads to the adjacent creek. These results show that soil physical properties that are relatively immutable can be used for predicting the location of potential hot spots of microbial activity at the landscape scale.

1. Introduction

The ability of floodplain and wetland soils to retain and/or reduce nutrients through microbial processing is important, due to concerns about nutrient loading and eutrophication in adjacent waterways (Ehrenfeld et al., 2003; Paerl et al., 2006; Paul and Meyer, 2001; Walsh et al., 2005). Wetland restoration and construction is increasingly used as a means of reducing inorganic nitrogen, especially nitrate (NO_3^-), in agricultural and urban runoff. However, reliable estimates of whole-site NO_3^- removal potential that are based on drivers of microbial activity in the soils and sediments of urban watersheds and associated wetland environments are needed to design or manage these systems effectively for the maximum reductive capacity. Nitrate removal via denitrification is a microbial process performed by a diverse group of heterotrophic and some autotrophic bacteria that are ubiquitous in the environment (Robertson and Groffman, 2015). These microbes use NO_3^- as an electron acceptor and convert it to gaseous forms, with N_2 as the final product in the reaction sequence. This process has been identified by environmental scientists and managers as a desirable way of converting a highly biologically reactive and potential ecologically damaging form of nitrogen (NO_3^-) to a highly inert form (N_2) that is already pervasive in the environment

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(Davidson et al., 2012).

Quantification and prediction of denitrification in soils is difficult. Denitrification occurs under sub-oxic (<0.2 mg O_2 L^{-1}, Seitzinger et al., 2006) conditions and requires NO_3^- (produced by nitrification under aerobic conditions) and labile carbon. The availability of these substrates and conditions are in turn controlled by a complex set of environmental variables, which exhibit high levels of spatial and temporal variability (Seitzinger et al., 2006). Although we know that hydrology is an important mediator of substrates and redox status in wetland soils, a number of variables can influence and interact with hydrologic regimes. Soil structure and texture determine pore connectivity and water-filled pore space, which in turn influences nutrient cycling within and between soil microsites (Castellano et al., 2013; Groffman and Tiedje, 1991; Morse et al., 2012; Parkin, 1987). Compacted soils with high clay content and low porosity appear to lack adequate exchange of substrates between aerobic and sub-oxic pores to couple nitrification and denitrification (Palta et al., 2014). On the other hand, given adequate soil moisture, high porosity and low tortuosity in coarser soils seem to facilitate exchange between pores supporting NO_3^- creation via nitrification and pores supporting NO_3^- removal via denitrification (Palta et al., 2014). Topographic positioning can affect drainage of a soil, and poorly drained, sub-oxic soils can either support high (Aulakh and Rennie, 1985; Groffman and Tiedje, 1989a, 1989b) or low (Palta et al., 2014) rates of denitrification, depending on NO_3^- availability.

Attempts to characterize the dynamic controls of water and soil physical properties on microbial processes, including nitrogen gas production, have often focused on water-filled pore space as an integrated predictor (e.g., Linn and Doran, 1984). A more comprehensive characterization of these dynamics requires quantification of a water retention curve that defines the relationship between the water content, θ, and the soil water potential, ψ (van Genuchten, 1980), but this is rarely done. Quantifying θ under different ψ for a given soil allows for determination of not only water-filled pore space under different moisture conditions, but also characterization of pore size distributions and hydraulic conductivity (i.e., exchange of water and solutes between pores) (Kosugi, 1996; van Genuchten, 1980; Yoon and Gimenez, 2012). Different soils often exhibit distinctive water retention curves, providing a basis for characterizing landscape variation in soil moisture dynamics.

The urban environment presents a unique challenge for predicting whole-site soil denitrification rates or denitrification potential. Studies examining urban and suburban sites in a variety of metropolitan areas have found significant effects of the urban environment on soil nitrogen and carbon pools and storage, but these effects vary considerably across the urban landscape due to patchiness of land use, vegetation, and soil types (Sawa et al., 2010). Urban soils are often composed of a mixture of materials differing from those of natural soils and/or are deeply modified in physical structure and chemical composition by human activity (De Kimpe and Morel, 2000); this makes prediction of soil microbial process rates as a function of soil structural components challenging. Here, we studied an urban floodplain site with a high level of spatial heterogeneity in soil texture and structure, hydrology, and topography (Palta et al., 2014). As with much of urban land, this site has a long history of human activity and modification. These heterogeneous soil conditions have important implications for soil chemistry and microbial processes.

A number of studies have identified both the pressing need for scaling denitrification information from small-scale point measurements to large (meters to kilometers) spatial scales, and the difficult challenge of scaling a process that is so highly variable at the microbial scale (Boyer et al., 2006; Groffman et al., 2009; Kulkarni et al., 2008; Van Breemen et al., 2002). Because small areas (hot spots) often account for a high percentage of N gas flux activity (Anderson et al., 2015; Duncan et al., 2013; Parkin, 1987), scaling point measurements to landscape or watershed scales must involve identifying these areas and their drivers, particularly for estimates of whole-site or whole-system N removal (Kulkarni et al., 2008; Tague et al., 2010; Vidon et al., 2010). The purpose of this study was (1) to identify the soil physical characteristics that best predict the highest (hot spots) and lowest (cold spots) actual and potential rates of denitrification within a small wetland complex in a park located on an abandoned urban site, and (2) use the spatial positioning of these characteristics relative to the location of stormwater flow to estimate whole-site potential for NO_3^- removal. We collected over 100 soil samples along transects through the site to characterize soil particle size distribution and organic matter content, and measured denitrification rates, denitrification potential and water retention characteristics on 19 of these samples. The latter subset was selected to represent the broad range of soil textures at the site. Previous research conducted at 14 locations in the same study site demonstrated that soil denitrification is tightly coupled to soil nitrification, and that soil porosity and connectivity likely facilitate this coupling (Palta et al., 2014).

We expected that the highest denitrification rates would be found in areas with water retention characteristics supporting simultaneous nitrification and denitrification within the soil matrix. We therefore hypothesized that soils with high macroporosity, intermediate water-holding capacity and pore sizes, and intermediate elevations would demonstrate the highest rates of denitrification at the site. Potential denitrification rates are measured in slurries under anaerobic conditions, where soil structure plays less of a role in mediating the redox status of pores and delivery of NO_3^- to denitrifiers. We therefore expected that potential denitrification rates would be mediated less by soil structure and more by NO_3^- availability and overall size and activity of the denitrifier community. Consequently, we hypothesized that the highest potential denitrification rates would occur at intermediate soil available NO_3^- concentrations, since very anaerobic soils have low NO_3^- production and therefore low denitrifier activity and populations, and very aerobic soils have high NO_3^- production, but bacterial populations have little need to produce denitrifying enzymes. Lastly, we expected that stormwater flowpaths mainly intersected with low elevation areas that are semi-permanently flooded, and therefore too anaerobic to support denitrification activity. Thus, we hypothesized that whole-site potential removal of NO_3^- in stormwater would be low.

2. Materials and methods

2.1. Site description

The study took place in the Teaneck Creek wetland complex, a small (0.2 km^2) freshwater floodplain ecosystem in northeastern New Jersey (NJ) that is part of the larger Hackensack River watershed (Fig. 1). Teaneck Creek is a former brownfield area, and most soils at the site are classified as Udorthents, organic substratum, 0–8% slopes (Soil Survey Staff, 1999). Soils in this category are filled and smoothed or otherwise extensively disturbed to a depth of 1 m or more, with buried tidal marsh deposits underneath, but are too variable in their properties to be classified to the next level. Soils located at an elevation of 4 m or more on the western side of the site (Fig. 1) are classified as Dunellen-Urban land complex, 15–25% slopes (Soil Survey Staff, 1999). These are coarse-loamy, mixed, active, mesic Typic Hapludults: very deep, well-drained soils, found on outwash plains and stream terraces. The numerous geomorphologic, biological, and hydrologic alterations at the site have led to high variation in soil profile composition at very small spatial