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Fate, mass balance, and transport of phosphorus in the septic system drainfields

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HIGHLIGHTS

- Less than 1% of effluent applied P leached from drainfield of a septic system.
- Approximately 95% of the effluent applied P remained in drainfield.
- Water extractable P increased in drainfield from <5 to >10 mg kg^{-1} after effluent dispersal.
- Effluent application for a year saturated 18% of P sorption capacity in drainfield.

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ABSTRACT

Septic systems can be a potential source of phosphorus (P) in shallow groundwater. Our objective was to investigate the fate, mass balance, and transport of P in the drainfield of a drip-dispersal septic system. Drainfields were replicated in lysimeters (152.4 cm long, 91.4 cm wide, and 91.4 cm high). Leachate and effluent samples were collected over 67 events (n = 15 daily; n = 52 weekly flow-weighted) and analyzed for total P (TP), orthophosphate (PO_4–P), and other P (TP − PO_4–P). Mean TP was 15 mg L^{-1} (84% PO_4–P; 16% other P) in the effluent and 0.16 mg L^{-1} (47% PO_4–P, 53% other P) in the leachate. After one year, 46.8 g of TP was added with effluent and rainfall to each drainfield, of which, <1% leached, 3.8% was taken up by St. Augustine grass, leaving >95% in the drainfield. Effluent dispersal increased water extractable P (WEP) in the drainfield from <5 to >10 mg kg^{-1}. Using the P sorption maxima of sand (118 mg kg^{-1}) and soil (260 mg kg^{-1}), we estimated that ~18% of the drainfield P sorption capacity was saturated after one year of effluent dispersal. We conclude that despite the low leaching potential of P dispersed with effluent in the first year of drainfield operation, a growing WEP pool in the drainfield and low P sorption capacity of Florida's sandy soils may have the potential to transport P to shallow groundwater in long-running septic systems.

1. Introduction

Understanding the fate of phosphorus (P) in septic systems, also known as onsite wastewater treatment systems, is especially important in Florida where 31% of the population relies on ~2.67 million septic systems to treat and discharge 1613 million liters of wastewater per day (Hall and Clancy, 2009; Meeroff et al., 2008). In old or improperly maintained systems, operational and functional failures can occur resulting in the release of undertreated septic tank effluent (STE) to the groundwater. The national failure rate (operational or functional) of septic systems exceeds 10% per year (EPA, 2003), with reported similar failure rates of 8–11% per year (equivalent to 208,000 to 286,000 systems) in Florida (Barranco and Hammonds, 2008). Further, over 50% of septic systems in Florida were installed more than 30 years ago when treatment standards were less rigorous (Hall and Clancy, 2009). These together with the sandy texture of soils and the presence of shallow groundwater in Florida can result in elevated concentrations of nutrients, pathogens, and organic contaminants from septic systems to groundwater.

Abbreviations: PO_4–P, orthophosphate –phosphorus; TP, total phosphorus; PSC, phosphorus sorption capacity; WEP, water extractable P; STE, septic tank effluent; PEBC, phosphorus equilibrium buffering capacity; EPC_o, equilibrium phosphorus concentration; S_{max}, sorption maxima; *K*, phosphorus binding strength; S_o, initial phosphorus sorption; PV, pore volume.

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Researchers have established a link between nutrient rich groundwater discharges and eutrophication in coastal and inland waters (Capone and Slater, 1990; Lapointe et al., 2015; Meinikmann et al., 2015). In Florida, Quyan and Zhang (2012) found that 53% of groundwater samples in areas with septic systems had total P concentrations exceeding the USEPA recommended ambient water quality criteria of 6–49 μg L^{-1} for rivers and streams, highlighting the potential for eutrophication from septic systems contaminated groundwater discharges. The fate of P in septic drainfields relies on a combination of biotic and abiotic processes such as sorption reactions, plant uptake, and mineralization/immobilization (Cherry et al., 1996; Lombardo, 2006). Researchers agree that P attenuation is largely the result of sorption and precipitation reactions with Al^{3+}, Fe^{2+}, Ca^{2+}, and Mg^{2+} (Lombardo, 2006; Roberston, 2012; Robertson and Blowes, 1995; Zanini et al., 1998). In addition, STE composition, pH, and redox potential can influence P sorption in drainfields (Eveborn et al., 2012; Roberston, 2012; Wilhelm et al., 1996; Xu et al., 2006; Zurawsky et al., 2004).

Phosphorus sorption capacity (PSC) is the ability of a soil to sorb P and can be measured using sorption isotherms (Nair et al., 2004; Ballard and Fiskell, 1974). Compared to fine-textured soils, Spodosols and other sandy soils typical of Florida have a higher risk of P leaching due to their limited PSC (Nair et al., 2004). Further, the PSC is lower in the surface horizons (A and E) and higher in the lower horizons (B) of Spodosols (Mansell et al., 1991). This can be problematic in drainfields which are typically constructed in raised beds or mounds above the soil surface and utilize the A and E horizons for STE dispersal and removal of effluent borne contaminants. During summer months, groundwater levels can reach depths of 60–102 cm below the surface and approach the A and B horizons (Soil Survey Staff, 2014), potentially increasing the risk of P transport by circumventing the lower soil profile. Seasonal factors such as elevated rainfall during the wet season can influence hydrologic conditions within the drainfield by decreasing residence time, increasing the vertical flow rate, and decreasing the distance between unsaturated and saturated zones due to elevated groundwater levels.

Previous research on P in mature septic systems (Robertson et al., 1998; Wilhelm et al., 1996; Zanini et al., 1998; Zurawsky et al., 2004) sampled STE and groundwater few times in a year, along with soil analysis to determine P minerals present within the drainfield. However, these studies did not investigate PSC of drainfields and mass balance of P in the drainfields. Thus, the objective of this study was to determine the fate, mass balance, and transport of P in the drainfield of a drip-dispersal septic system.

2. Material and methods

2.1. Lysimeter construction

Three replicate drainfields (1.78 m^2) were constructed by packing commercial sand and soil in lysimeters (152.4 cm long, 91.4 cm wide, 91.4 cm high, with 1:1 side slope) (Supplementary Fig. S1). The study site was located at the Gulf Coast Research and Education Center of the University of Florida in Wimauma, Florida, USA. Soil used in the lysimeter was loamy sand (sand: 86.5%, silt: 8.5%, clay: 5%) (Supplementary Table S1) and classified as Spodosol, which was collected from the A horizon (Ap: 0–17 cm) and partial A/E horizon (18–30 cm) of a zolfo fine series (sandy siliceous, hyperthermic Oxyaquic Alorthods). Soil and commercial sand were air-dried for 7 d and sieved using a 2-mm sieve (US sieve No. 10) before packing in the lysimeters.

Each lysimeter was constructed by adding 7.6 cm of a commercial sand (66 kg) and pea gravel (133 kg) mixture (bulk density 1.91 g cm^{-3}) at the bottom of each lysimeter (Supplementary Fig. S1). Then, 30.5 cm layer of soil (626 kg) was added followed by 30.5 cm layer of commercial sand (540 kg). A drip line (3 emitters, 30.5 cm apart) was placed on top of the commercial sand layer to disperse STE and was covered with 15.3 cm of sand (157 kg) before planting St. Augustine (*Stenotaphrum secundatum*) grass on top and sides of the lysimeters to mimic a typical drip-dispersal drainfield. In each lysimeter, a hole was drilled at the bottom and a plastic pipe was attached to collect leachate over one year (Jan 2013–2014). Each drainfield used in the study received 9 L day^{-1} of STE (equal to the maximum rate of 32.29 L m^{-2} day^{-1} for Florida loamy sand soils) in six doses at four hour intervals. The STE used in the study was produced from onsite graduate housing and office buildings that serve ~50 people per day. More details about lysimeter construction and management can be found in De and Toor (2015, 2016).

2.2. Water sample collection and analysis

Leachate and STE samples were collected over 67 leaching events (15 daily events followed by 52 weekly flow-weighted). Subsamples filtered through 0.45-μm filter paper (Pall Corporation, Ann Arbor, MI) were analyzed for orthophosphate (PO_4–P) using Auto Analyzer 3 (AA3, Seal Analytical, Mequon, WI, USA) with EPA Method 365.1. For total P (TP) analysis, unfiltered subsamples were digested using persulfate digestion (Ebina et al., 1983), followed by PO_4–P analysis as described above. Other P was calculated as the difference between TP and PO_4–P and was assumed to be organic and particulate P. Quality control, sample duplicate, reagent blank, laboratory fortified blank (LFB), continued control verification (CCV), and spikes were strictly adopted for inspecting quality assurance and quality control (QA/QC) of analysis. The detection limit of PO_4–P and TP was 0.002 mg L^{-1}.

2.3. Lysimeter dissection and soil sample collection

Background soil and commercial sand samples were collected prior to the drainfield packing. After one year of STE application, lysimeters were dissected to collect soil and commercial sand samples within the drainfield to determine the distribution and accumulation of P at various depths and locations. The metal and wood frame of the lysimeter were first cut. Then, each lysimeter was divided into four zones consisting of 36 grids (each grid was 15 cm to 15–20 cm; see Supplementary Fig. S2). After removing 2–4 cm of soil or sand in the exposed area, a composite sample (500–600 g) was collected from each grid in relation to three emitters (side, center, side) and then a composite was made. Samples were passed through a 2-mm sieve, placed in a plastic zip lock bag, and stored at 4 °C until analysis.

2.4. Soil and plant analysis

Water extractable P (WEP) content of the soil and sand before and after STE application was measured using soil to solution ratio of 1:25 (Self-Davis et al., 2009). Soil and sand samples were analyzed for total Ca and Mg using acid digestion followed by inductively coupled plasma-optical emission spectroscopy (ICP-OES) analysis with EPA Method 200.7. Details of pH, electrical conductivity (EC), bulk density, and particle density measurement are included in the supplementary information. All of the St. Augustine grass clippings were collected approximately monthly ($n = 10$ for each lysimeter) and weighed before drying at 105 ± 2 °C. After drying, clippings were ground using a Wiley mill (Arthur H. Thomas Co., Swedesboro, NJ) and analyzed for TP on ICP-OES using EPA method 200.7.