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Nutrient Leaching When Soil Is Part of Plant Growth Media

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Abstract: Soils can serve as sorbents for phosphorus (P), negating the need for artificial sorbents. The purpose of this study was to compare soils with different properties for their effect on nutrient levels in effluent. Four soils were mixed with sand and packed into columns 0.5 m long, with or without compost on the surface. Infiltration and effluent concentrations were measured before and after growing plants [Buffalograss (*Buchloe dactyloides* (Nutt.) Engelm.) and bluegrama grasses (*Bouteloua gracilis* H.B.K.) and red clover (*Trifolium pratense* L.)]. The growth media with compost at the surface had higher nutrient levels than the media without the compost, but the final effluent nitrate concentrations post-harvest were significantly lower for columns with the compost blanket (59 vs. 86 mg L^{-1}). All of the nitrate concentrations were high (many >100 mg L^{-1}) due to mineralization and nitrogen fixation. The final effluent P concentrations before planting were significantly higher in the soil with the most sand (0.71 mg L^{-1}), and after harvest in the mixture that contained the high soil P levels (0.58 mg L^{-1}). Some soils (high in aluminum or calcium) were adequate sorbents for P without additions of other sorbents, but soils often generated too much nitrate in effluent.

Keywords: bioretention cell; nutrient leaching; soil sorbents

1. Introduction

Reagent-grade sand is often a large component of engineering soil mixes used in bioretention cells where plants are grown; however, sand has low water holding capacity, cation exchange capacity, nutrient levels, and nutrient sorption capacity [1–3] than soil. Sometimes, sorbents [4,5] are added to sand to increase P retention, especially in filters in which no plants are growing. Unfortunately, sorbents used in these filters may not be suitable for filter systems where plants are grown [6].

Soils with varying P sorption capacity can be used as sorbents in engineered mixes [3,7,8]. Just a little fine-textured soil, clay, or oxides of aluminum (Al) or Fe decreased P leaching compared with sand substrate containing organic material [1,9,10]. Kaolinite and iron (Fe) oxides were the best P sorbents at lower pH whereas illite and smectite clays were better sorbent at mid to higher pH [11,12].

Soils can be a source or sink for nitrogen [7,13]. High levels of organic matter can be mineralized, resulting in higher levels of nitrate. If the organic matter has a high carbon to nitrogen ratio, nitrate can be immobilized. Ammonium can be sorbed to clays or nitrified. Wet soil can have pockets of reducing conditions resulting in denitrification [14–16] and loss of nitrate. Plant uptake [17,18], root turnover, and nitrogen fixation by legumes also impact levels of nitrate and ammonium in soils.

The goal of the study was to determine whether soils differed in their ability to decrease the leaching of P or nitrate when made part of engineered plant growth media. This study is part of a series of studies examining bioretention cell mixtures on nutrient leaching. Addition of biochar and perlite or dolomite (3% by volume) did not retain P [19]. Addition of iron filings (3% by volume) resulted in partial cementation of the sand or soil mixes [6]. Addition of manure compost resulted in unacceptable leaching loss of nitrate [19]; however, layering the compost on top rather than mixing throughout reduced nitrate leaching.

2. Materials and Methods

2.1. Experiment

Four soils were chosen with varied amounts of clay, organic carbon, and carbonates (Table 1), properties that might have an impact on P sorption. One soil had some carbonates and sand but low amounts of organic carbon (Storden: Fine-loamy, mixed, superactive mesic Typic Eutrudept). Another soil was high in clays that had Al-hydroxy interlayer material (Sac: Fine-silty, mixed, superactive, mesic Oxyaquic Hapludoll). The third soil had moderate levels of organic carbon (Killduff: Fine-silty, mixed, superactive, mesic Dystric Eutrudept). The final soil had moderate amounts of organic and inorganic carbon and clay (Harps: Fine-loamy, mixed superactive, mesic Typic Calciaquoll). Storden had 0.25 g/kg inorganic carbon and Harps had 1.89 g/kg, but the other soils did not have inorganic carbon. Soil classification is from Soil Survey [20]. The disturbed soils were dug up and partially-broken up by hand but not sieved.

Table 1. Properties of soils used in the study. Nutrient levels were mg kg^{-1}.

Soil	Fe-DTPA [1]	P_{M3}	Al_{M3}	Fe_{M3}	Ca_{M3}	OC [1]	IC [1]	NO_3	NH_4	Sand	Clay	pH
						g/100 g				g/g	g/g	
Storden	11	1.9	65.1	6.9	367	1.28	0.25	11.9	2.6	0.51	0.20	6.9
Sac	44	2.7	92.8	13.6	425	1.95		34.6	9.0	0.03	0.37	6.4
Killduff	71	13.6	64.5	29.6	368	2.38		16.7	4.5	0.02	0.40	6.9
Harps	32	4.6	9.1	15.1	1185	2.77	1.89	20.0	4.4	0.29	0.35	7.3

Notes: [1] Iron DTPA was diethyenetriaminepentaacetic acid extraction; OC is organic carbon; IC is inorganic carbon.

The study consisted of eight soil mixture treatments. The first four mixtures were made of 20% soil mixed with 80% sand by volume. The other four mixtures were 15% soil mixed with 80% sand, and topped by 5% compost blanket. The sand used in the soil mix was 1% very coarse (1–2 mm), 18% coarse (0.5–1 mm), 61% medium (0.25–0.5 mm), and 20% fine sand (0.1–0.25 mm), determined from sieving. Although a low nutrient compost was sought, the compost was higher in nutrients than desired (51 mg kg^{-1} ortho phosphate, 16 g kg^{-1} total nitrogen). The packing densities of each component of each mix was used to determine the mass fractions of the whole mix. There were three replicates for each of the eight treatments (four soils mixes, with or without compost blanket) for a total of 24 columns. The columns were 15 cm diameter and 50 cm long, each with a drainhole at the bottom. At the bottom, there was a 2.5 cm layer of aquarium gravel above the drainhole to allow for better drainage.

Disk infiltrometers (7.6 cm diameter) were used to determine saturated (first) and then unsaturated infiltration (−3 cm head) in succession [21,22] and to leach the columns. Infiltration rate was determined from the steady state rate of the water level drop multiplied by the cross sectional area of the infiltrometer and divided by the cross-sectional area of the column. Time to initial drainage was recorded. The first container of effluent under saturated infiltration was collected to determine the early leachate due to flow in large soil pores. The final container of effluent under unsaturated infiltration was collected to determine the delayed matrix leachate (excluding larger soil pores). These will be called "saturated effluent" and "unsaturated effluent". Saturated and unsaturated effluent were saved for analysis of nitrate and total P. Total load in the effluent was determined by multiplying saturated or unsaturated concentration of P or nitrate-N by the saturated or unsaturated effluent volume. Then the load in saturated and unsaturated effluent components were added together.

Buffalograss and bluegrama grasses were planted 11 February 2015 in all columns. The grasses were sown at total 0.8 g in each column. Red clover was planted 12 February 2015, and then thinned to 20 plants in each column 18 February 2015. The columns were watered with tap water through 3 March 2015. Seven brooder clamp light reflectors (Bayco, Inc., Wylie, TX, USA) were used with

6500 K daylight compact fluorescent bulbs. A timer was used to set for twelve hours of daylight. The temperature range was about 18 to 28 °C. Then they were watered periodically with nutrient solution to simulate nutrient loads in stormwater. In total 189 mg N and 81 mg P were added per column in the nutrient solution.

After harvesting the plants on 7 April 2015 for dry matter and rooting depth, the saturated and unsaturated infiltration was repeated. Saturated and unsaturated effluents were again collected to determine nitrate and total P concentrations and total loads. Soil cores were taken by pushing brass cylinders (5.3 cm inner diameter and 6 cm long) into the surface of each column. The samples were dried at 105 °C to determine bulk density [23].

2.2. Analyses for the Study

Soil particle size was determined by the hydrometer method combined with sieving for total sand. A 1:1 water pH was determined. The effluent was analyzed for nitrate plus nitrite nitrogen with a Lachet autoanalyzer that used Cd reductions [24,25]. Total P of the effluent was determined using flow injection analysis [26] after acid-persulfate digestion. Total carbon and nitrogen of the soils, sand, and compost were determined by dry combustion with a Fisons NA1500 Elemental Analyzer. The sand, soils, and compost were extracted with Mehlich 3 (ICP) [27] to determine P, Ca, Mg, Fe, and Al. Iron was also extracted with Diethyenetriaminepentaacetic acid (DTPA) [28]. Volume fractions, bulk densities and analyses of the sub-components were used to determine mixture compositions.

Maguire and Sims [29] used the degree of P saturation (DPS) ratio for Mehlich-3 extraction P/(Al + Fe) for soils with pH < 7. Higher values are associated with better crop growth but potentially more leaching potential for P. The DPS ratio was determined as well as the alternate ratio [30–32], P/Ca, since it is better for soils with pH > 7.

Analysis of variance was used to compare whole treatment effects of soil in the mix or with/without compost blanket. Tukey's test was used to compare soil mixes. Differences were considered significant at $p = 0.05$.

3. Results and Discussion

3.1. Soil Mix Composition

When diluted by the sand and compost blanket, the soil nutrient differences were less apparent (Table 2) because of the much higher levels of organic carbon and nitrate in the compost blanket. The Sac soil mix had significantly higher levels of Al, which likely sorbed some of the P. The Killduff soil mix had higher levels of Mehlich-3 extractable P and DTPA-extractable Fe, and the Sac soil mix had higher levels of NO_3 and NH_4, which may represent fertilization differences. Lower ratios (P over Al + Fe or P over Ca) indicated greater potential sorption capacity for P.

Table 2. Properties of soil mixes averaged across those with and without compost blankets.

Soil Mix	Fe-DTPA [1]	P_{M3} [1]	$P_{M3}/(Al_{M3} + Fe_{M3})$	P_{M3}/Ca_{M3}	OC [1]	TN [1]	NO_3	NH_4
	mg/kg	mg/kg			g/100 g	g/100 g	mg/kg	mg/kg
Storden	22c [2]	1.2b	0.049b	0.0033b	0.76a	0.06a	14a	0.72c
Sac	26b	1.1b	0.044b	0.0034b	0.77a	0.06a	13a	1.26a
Killduff	29a	2.2a	0.090a	0.0064a	0.81a	0.06a	12a	0.81b
Harps	25bc	1.3b	0.074a	0.0031b	0.84a	0.07a	11a	0.81b

Notes: [1] Iron DTPA was diethyenetriaminepentaacetic acid extraction. The $_{M3}$ was Mehlich-3 extraction. OC is organic carbon, TN is total nitrogen; [2] Treatments followed by the same letter in a column were not significantly different at $p = 0.05$.

When averaged across soil mixes (Table 3), those with a compost blanket had significantly higher readily available Fe (DPTA), ortho phosphate, DPS and ratio of P over Ca, organic carbon, total nitrogen, and nitrate. The higher ratios for the columns with the compost blanket indicated slightly less sorption capacity for P.

Table 3. Properties of soil mixes with or without compost blankets averaged across soils.

Compost Blanket	Fe-DTPA [1]	P_{M3} [1]	$P_{M3}/(Al_{M3} + Fe_{M3})$	P_{M3}/Ca_{M3}	OC [1]	TN [1]	NO_3	NH_4
	mg/kg	mg/kg			g/100 g	g/100 g	mg/kg	mg/kg
No	25b [2]	1.1b	0.051b	0.0033b	0.67b	0.06b	2.9b	0.87a
Yes	27a	1.7a	0.077a	0.0048a	0.92a	0.07a	21.8a	0.92a

Notes: [1] Iron DTPA was diethyenetriaminepentaacetic acid extraction. The $_{M3}$ was Mehlich-3 extraction. OC is organic carbon, TN is total nitrogen; [2] Treatments followed by the same letter in a column were not significantly different at $p = 0.05$.

3.2. Infiltration, Bulk Density, Plant Growth

The pre-plant saturated infiltration rates (Tables S1 and S2) were not significantly different among the soil mixes or between treatments with and without the compost blanket (2.3 cm h^{-1}). The unsaturated infiltration rates were not significantly different among the soils, but the columns with the compost blanket (1.2 cm h^{-1}) had significantly slower infiltration rate than the columns without the compost (5.5 cm h^{-1}). Time to initial drainage was not significantly different among the soils, but columns with compost blanket had significantly longer time to initial drainage (95 min) than columns without compost (52 min). The compost blanket was dry before starting the study, and possibly somewhat water repellent (not tested), which might have slowed the initial infiltration. Post-harvest saturated (4.5 cm h^{-1}) and unsaturated (5.0 cm h^{-1}) infiltration rates and time to first drainage (19 min) were not significantly different among the soils or whether a compost blanket was present (Tables S1 and S2).

Surface bulk densities (1.66 Mg m^{-3}) or rooting depths (0.27 m) were not significantly different among the soil mixes or whether or not a compost blanket was present (Table S3). Logsdon and Sauer [19] showed higher bulk density for engineered mixes that did not include soil. There were no significant differences in above-ground dry mass per column of either grass (1.1 g) or clover (7.4 g) among the soil mixes or whether or not a compost blanket was present (Table S3).

3.3. Compost Blanket Effect on Nutrient Leaching

Even though overall levels of nutrients were higher in the columns that had a compost blanket (Table 3), there were no significant increases in effluent nutrient losses either pre-plant or post- harvest, for total P or nitrate in columns with and without the compost blankets (Tables S4 and S5). Post-harvest unsaturated nitrate levels were significantly lower for the columns with compost blankets (59 mg L^{-1}) than for those without (86 mg L^{-1}), in spite of higher nutrient levels in the compost blanket. Hsieh and Davis [33] and Logsdon and Sauer [19] showed that a compost blanket reduced initial nitrate losses compared with mixing the compost into the plant growth media.

3.4. Nitrate in Effluent as Affected by Soil

The pre-plant first flush of effluent (Table 4) contained significantly higher nitrate levels for the Sac soil mix (74 mg L^{-1}) than for the Storden soil mix (12 mg L^{-1}). The Sac soil mix had significantly higher levels of soil ammonium than did the Storden soil mix (Table 2), indicating perhaps that fertilizer application was more recent at this site.

Table 4. Nitrate in saturated and unsaturated effluent of soil mixes (across compost treatments), before planting and after harvest. Also calculated total nitrate load in preplant and post-harvest effluent, based on outflow volumes for saturated and unsaturated effluent.

Soil Mix	Pre NO_3sat	Pre NO_3unsat	Pre NO_3 Load	Post NO_3sat	Post NO_3 Unsat	Post NO_3 Load
	mg/L	mg/L	mg	mg/L	mg/L	mg
Storden	15b [1]	26a	28a	221ab	70a	253ab
Sac	68a	36a	55a	263a	79a	270a
Killduff	46ab	17a	42a	159bc	63a	190ab
Harps	64ab	41a	65a	114c	75a	128b

Note: [1] Treatments followed by the same letter in a column were not significantly different at $p = 0.05$.

The post-harvest nitrate concentration in the saturated effluent was significantly higher for the Sac soil mix than for Killduff and Harp mixes, whereas the nitrate load was higher for Sac mix than for Harps mix. Nitrification of the higher ammonium levels in the Sac soil (Table 2) likely occurred during the study. All effluent nitrate levels were high after harvest (>50 mg L^{-1}), with loads significantly higher for post-harvest than for preplant (Table 4). Nitrogen fixation, mineralization, and pre-sampling fertilizer additions might have contributed to the high effluent nitrate.

Studies on bioretention cells [3,33] often show low effluent nitrate concentrations (<1 mg L^{-1}). Bratiers et al. [34] reported lower nitrate concentrations if plants were grown compared to no plants. Logsdon and Sauer [19] showed that amount of nitrate in the engineered mix was significantly correlated with the concentration of nitrate in the first saturated effluent.

3.5. Total P in Effluent as Affected by Soil

Post-harvest total P in effluent was not significantly affected by the presence of compost blankets, but soils caused differences. The Killduff soil mix had significantly higher levels of extracted ortho phosphate (Mehlich-3) than the other soils (Table 1), which was reflected in the ratios. Before planting (Table 5), the Storden soil mix had significantly higher P concentrations in the unsaturated effluent as well as significantly higher P load lost (combined saturated and unsaturated). Storden soil had more sand and less clay (Table 1). Since clay minerals could reduce P leaching [10,12], the greater P leaching in the Storden soil could be due to its greater sand content. Post-harvest, the Killduff soil mix also had significantly higher total P concentrations in effluent and total load loss than the other soils. Maguire and Sims suggested the Mehlich-3 extracted DPS ratio greater than 0.1 to 0.2 (depending on soil) was enough to increase P leaching [29], whereas Mukherjee et al. determined a cutoff ratio of 0.067. The Killduff and Harps mixes were over the 0.067 levels. The higher leaching was only reflected in the effluent from Killduff mix columns, and only after harvest. Harps mix was high in calcium carbonate, reducing the P/Ca ratio compared with Killduff soil mix. Calcium carbonate can reduce P leaching [35]. The Sac, Killduff, and Harps soil were moderately high in clay (Table 1), which can also sorb P [3,10].

Table 5. Total phosphorus (TP) in saturated and unsaturated effluent of soil mixes (across compost treatments), before planting and after harvest. Also calculated total phosphorus load in preplant and post-harvest effluent, based on outflow volumes for saturated and unsaturated effluent.

Soil Mix	Pre Plant TPsat	Pre Plant TPunsat	Pre Plant P Load	Post Harvest TPsat	Post Harvest TPunsat	Post Harvest P Load
	mg/L	mg/L	mg	mg/L	mg/L	mg
Storden	0.24a [1]	0.71a	0.64a	0.08b	0.05b	0.11b
Sac	0.09a	0.40b	0.23b	0.09b	0.07b	0.11b
Killduff	0.10a	0.09c	0.13b	0.41a	0.37a	0.58a
Harps	0.10a	0.10c	0.12b	0.07b	0.07b	0.09b

Note: [1] Treatments followed by the same letter in a column were not significantly different at $p = 0.05$.

4. Summary and Conclusions

The effluent nitrate concentrations were higher after plants had been grown on the soil mixes than before, perhaps due to nitrogen mineralization in the soil. Although the compost blanket added higher nutrient loads to the mix, effluent concentrations with the compost blankets were not significantly different from those without the compost blankets. After harvest, the unsaturated effluent had significantly lower nitrate levels from the columns with compost blankets than the columns without the compost blankets.

Soil mixes did show differences in effluent total P concentration, probably related to aluminum, carbonates, and clays in the soils. At least for P leaching, sorption to soils in the mixes was adequate in the absence of inorganic non-soil P sorption products. The soils were not harmful to plant growth as sorbent materials could be [6]; however, excess nitrate leaching occurred over time. Overall, it is recommended that bioretention cells and other plant growth media include soil as a component to reduce P leaching.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4441/9/7/501/s1, Table S1. Saturated and unsaturated infiltration rates and time to initial drainage for the soil mixes (across compost treatments) for pre-plant and post-harvest; Table S2. Saturated and unsaturated infiltration rates and time to initial drainage for the compost treatments (across soils) for pre-plant and post-harvest; Table S3. Mass of grass and clover, surface bulk density, and root depth for the soil mixes averaged across those with and without compost blankets; Table S4. Nitrate in saturated and unsaturated effluent of compost blanket treatment (across soils), before planting and after harvest. Also calculated total phosphorus load in preplant and post-harvest effluent, based on outflow volumes for saturated and unsaturated effluent; Table S5. Total phosphorus in saturated and unsaturated effluent of compost blanket treatment (across soils), before planting and after harvest. Also calculated total phosphorus load in preplant and post-harvest effluent, based on outflow volumes for saturated and unsaturated effluent.

Conflicts of Interest: The author declares no conflict of interest.

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