Effects of Sand Depth on Domestic Wastewater Renovation in Intermittently Aerated Leachfield Mesocosms

José A. Amador[1]; David A. Potts[2]; Erika L. Patenaude[3]; and Josef H. Görres[4]

Abstract: The depth of soil below the absorption trench of a septic system is considered an important factor in protection of groundwater. We examined the effects of depth on the ability of intermittently aerated sand-filled leachfield mesocosms to renovate domestic wastewater. Mesocosms ($n=3$) consisted of lysimeters with a headspace O_2 concentration maintained at 0.21 mol/mol and containing 7.5, 15, or 30 cm of sand that were dosed with septic tank effluent every 6 h for 328 days (12 cm/d). Sand depth had no effect on pH, dissolved O_2, PO_4, NH_4, or BOD_5 levels in percolate water. Nitrate levels in percolate water were higher for 30 cm than for 7.5 and 15 cm during the first 70 d of the experiment, after which no differences were observed. Time-averaged removal rates of N, P, fecal coliform bacteria, and BOD_5 were 22–28, 13–18, 81–92, and 81–99%, respectively, and were unaffected by depth. Wastewater renovation in intermittently aerated leachfield mesocosms appears to take place in a narrow zone ($\leq$7.5 cm) below the infiltrative surface, with the medium below contributing little to renovation.

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CE Database subject headings: Wastewater management; Septic tanks; Sand; Nutrients; Biochemical oxygen demand; Bacteria; Aeration.

Introduction

Improvement of water quality in conventional on-site wastewater treatment systems (OWTSs) takes place both in the septic tank, where removal of solids, oil and grease, and some anaerobic digestion takes place, and in the absorption field, or leachfield, where percolation of septic tank effluent (STE) through the soil allows for microbial, organic, and inorganic constituents in effluent to interact with soil processes. For example, net removal of P in the leachfield can take place via abiotic processes, through sorption and binding of PO_4 to oxides of aluminum and iron in acidic soils, and through formation of insoluble precipitates in alkaline soils (Beal et al. 2005; Robertson 2003; Zanini et al. 1998). Net nitrogen removal, when it occurs, results from the combined activities of bacteria that mineralize organic N to ammonium, oxidize it to nitrate, and reduce it to N_2 and N_2O, gases that are readily lost to the atmosphere (USEPA 2002). Pathogenic organisms are thought to be removed from STE by a combination of processes that include physical filtration, adsorption to soil particles, predation by soil fauna, and competition with resident microflora (Hagedorn et al. 1981; Reddy et al. 1981).

The relationship between depth and particulate and dissolved pollutant removal in leachfield soil is not particularly well understood or quantified. The extent of renovation of STE in leachfield soil is thought to be proportional to soil depth (Jenssen and Siegrist 1990). For example, in a pilot-scale study of intermittent sand filters with depths of 30, 45, and 60 cm, Peeples et al. (1991) found that levels of BOD_5 decreased significantly as depth increased. In contrast, levels of NH_4 were not significantly different at 30 and 45 cm, but were significantly lower at 60 cm (Peeples et al. 1991). Stevic et al. (1999) found a significant reduction in the number of *E. coli* from STE with medium depth, with 99% of the bacteria removed in the top 12 cm of 80 cm long columns packed with round light weight aggregate, with higher removal observed at greater depths.

In the case of chemical and biological processes—that are controlled by interactions with the surfaces of soil particles, microorganisms, and/or enzymes—greater depth is thought to translate into a longer residence time within soil pores, increasing the probability of an occurrence of the appropriate process. Filtration theory predicts that retention of particulates in porous media—such as soil—is a first-order process, with the concentration of particulates decreasing exponentially with depth (Acostas and Castillejos 2000). Thus, passage of STE through a greater depth of soil increases the probability that pathogenic organisms encounter pores with dimensions smaller than their own diameter, or that they pass through sufficiently narrow pore necks whose surfaces they may diffuse to and subsequently adsorb on. These assumptions form part of the rationale behind restrictions on the separation distance between the infiltrative surface of the absorption trench and the seasonal high groundwater table by local and regional regulatory agencies in the United States and elsewhere.

In a previous, laboratory-scale study, we found that intermittent aeration of leachfield mesocosms filled with 30 cm of quartz

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Table 1. Mean ($n=10$) Values of Water Quality Parameters and Loading Rates of Septic Tank Effluent (STE) Inputs into Leachfield Mesocosms

Parameter	Mean value (s.d.)	Loading rate
Temperature (°C)	18.1 (1.6)	NA
pH	6.8 (0.2)	NA
Dissolved O_2 (mg/L)	0	NA
BOD_5 (mg/L)	230 (48)	27.6 $g/m^2/d$
Total N (mg N/L)	47.5 (6.3)	5.7 g $N/m^2/d$
NO_3 (mg N/L)	0.0	0
NH_4 (mg N/L)	37.1 (9.3)	4.5 g $N/m^2/d$
Total P (mg P/L)	7.9 (1.9)	0.9 g $P/m^2/d$
PO_4 (mg P/L)	3.9 (1.2)	0.5 g $P/m^2/d$
SO_4 (mg S/L)	6.9 (3.7)	0.8 g $S/m^2/d$
Fecal coliforms (CFU/100 mL)	5.89×10^5	7.07×10^8 $CFU/m^2/d$

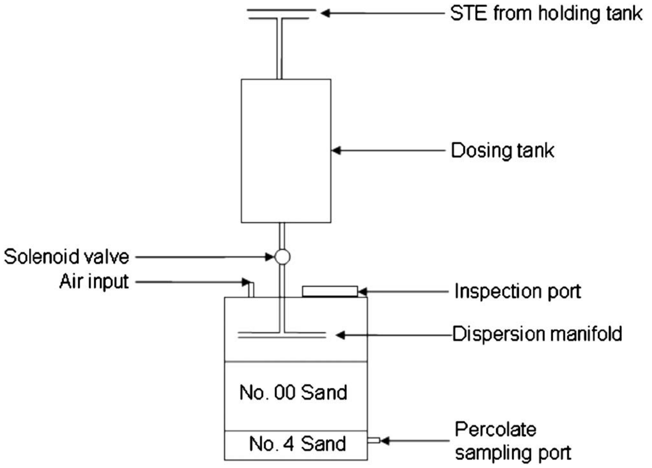

Fig. 1. Schematic diagram of experimental mesocosms used to study effects of sand depth on STE renovation

sand improved the removal of N, BOD_5, and fecal coliform bacteria relative to unaerated soil (Potts et al. 2004). These improvements were observed in the absence of a conventional restrictive layer—or biomat—and for N removal were apparent only at high hydraulic loads (12 cm/d) (Potts et al. 2004). The effects of aeration were presumed to be due to removal of electron acceptor limitations by the periodic introduction of O_2 following application of anaerobic wastewater to the infiltrative surface. This would allow for the establishment of ammonium oxidation to nitrate—a necessary step prior to denitrification—and support a larger community of microbivorous fauna thought to be involved in pathogen removal, as well as more efficient and complete utilization of BOD_5. The structure and function of the biotic community of these soils differed markedly, with a larger and more diverse microbial and faunal community found in intermittently aerated soil (Amador et al. 2006). Of particular interest with respect to STE renovation was the presence of larger numbers of microorganisms and microbivorous fauna in soil at 0–4 cm than at 4–13 cm in intermittently aerated soil, which indicates that biological activity is concentrated in a fairly narrow band below the infiltrative surface. Together, these results suggest that intermittent aeration may reduce the depth requirements for successful renovation of STE in leachfield soil.

The objective of the present study was to assess the extent to which water quality improvements in intermittently aerated leachfield soil depend on soil depth.

Materials and Methods

Facility

The study was conducted at a domestic wastewater research facility in southeastern Connecticut, described previously (Potts et al., 2004). Briefly, it consists of a laboratory adjacent to a two-story, two-family home built in 1983. The home was fitted with a conventional septic system that was installed in 1996. The septic tank had a maximum capacity of 4,733 L and was not pumped during the course of the study. The home was inhabited continuously by three to six people. A summary of the nutrient loading rates and measured chemical, microbiological, and physical characteristics of septic tank effluent during the course of the experiment is found in Table 1.

A schematic diagram of the experimental setup is shown in Fig. 1. All of the effluent from the septic tank was diverted to a pump station and stored in an air-tight high-density polyethylene (HDPE) tank (1,325 L maximum capacity) housed in a climate-controlled (17 to 19°C) room above the laboratory. The contents of the tank were mixed every 2 h using a pump. STE from the tank was pumped through a PVC manifold to a series of dosing tanks in the laboratory. Cylindrical HDPE dosing tanks (30.5 cm inner diam, 45.7 cm height) had a maximum capacity of 38 L and were dosed every 6 h. Dosing was regulated using solenoid valves. Dosing tank overflow was allowed to drain completely until the desired dose volume was retained. STE from the dosing tanks flowed by gravity into a series of mesocosms (described below).

Depth Treatments

We determined the effects of sand depth with mesocosms built using cylindrical HDPE tanks (43.2 cm inner diam, 45.7 cm height) with fittings for air and water inputs, sampling of percolate water, and an inspection port (Fig. 1). STE was delivered to the surface of the sand through a perforated horizontal, 1.91 cm diam PVC manifold to attenuate the impact of delivery. STE was applied to the mesocosms at a rate of 12 cm/d for the duration of the experiment.

Treatments consisted of 7.5, 15, or 30 cm of silica sand (No. 00; diam 0.71–0.21 mm; uniformity coefficient <1.6; U.S. Silica Co., Berkeley Springs, WV) placed on top of 7.5 cm of No. 4 silica sand (diam 4.75–1.40 mm; uniformity coefficient <1.8). The volume above the infiltrative surface constituted headspace. Each treatment was replicated three times. A blower was used to introduce ambient air at regular intervals into the headspace of all mesocosms to maintain an O_2 level of 0.20–0.21 mol/mol, which resulted in a pressure of ~2.5–6.7 kPa. The experiment was run continuously Sept. 11, 2003 to Aug. 4, 2004 (328 d). Percolate water samples were taken 14, 42, 70, 98, 132, 160, 188, 216, 244, 272, 300, and 328 days after the start of the experiment.

Sampling, Processing, and Analysis

Water sampling and processing procedures are described in Potts et al. (2004). Briefly, STE samples were collected from a valve in the input stream (purged by allowing 1–2 L of STE to flow through) and placed in autoclaved plastic bottles. Samples of percolate water from the mesocosms were collected in 3 L Tedlar

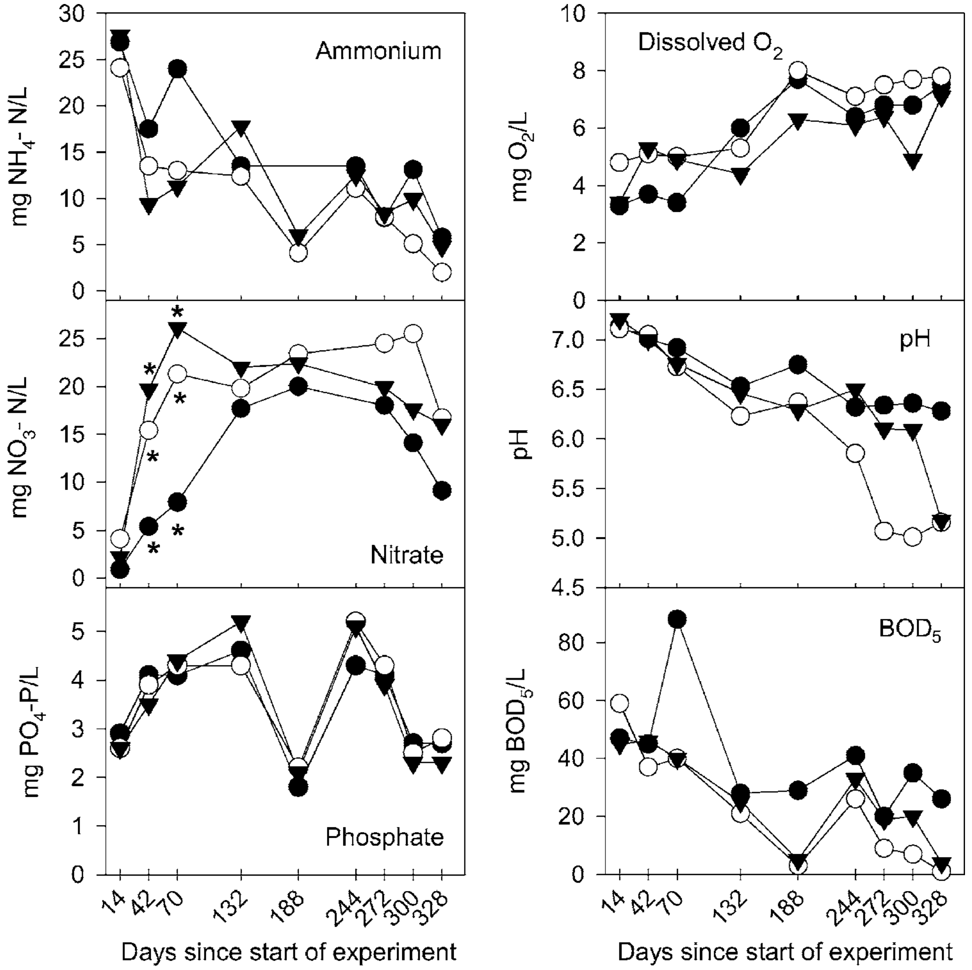

Fig. 2. Percolate water pH and concentration of BOD$_5$, dissolved O$_2$, NH$_4$, NO$_3$, and PO$_4$ as a function of time in intermittently aerated mesocosms with different sand depths. Values are means ($n=3$). (*) indicates values were significantly different.

bags (2 mil thick, SKC, Inc., Eighty Four, Pa.). The bag was connected to the mesocosm outlet using Tygon tubing. To ensure that water samples were exposed to an atmosphere with the same composition as that found in the mesocosms, a connection was made from the headspace of each mesocosm to the drainage line connected to the sampling bag. Sampling of water from the mesocosms started coincident with a dosing event.

All water samples were analyzed immediately for dissolved oxygen (DO) using the azide modification of the Winkler titration method (APHA 1998), and for the presence of Fe^{2+} using EM Quant Iron (Fe^{2+}) test strips (EM Industries, Inc., Gibbstown, N.J.), with the remaining volume kept at 4 °C during transport to the laboratory in Kingston, RI ($\sim$1 h). Unfiltered water samples were used to determine 5-day biochemical oxygen demand (BOD$_5$) using manometric respirometry (OxiTop BOD system; WTW, Fort Myers, Fla.), pH (model UB-10 pH meter; Denver Instruments, Denver, Colo.), fecal coliforms and *E. coli* [membrane filtration procedure; APHA (1998)], and total N (TN) and total P (TP) content using the persulfate digestion method (APHA 1998). The remaining sample was filtered (GF/F, 25 mm diam; Whatman Intl. Ltd., Maidstone, England) and analyzed for NH$_4^+$, NO$_3^-$, PO$_4^{3-}$ using an automated nutrient analyzer (Flow Solution IV, Alpkem, College Station, Tex.) and for SO$_4^{-2}$ using the barium chloride turbidimetric method (APHA 1998).

STE samples were analyzed in triplicate on every sampling date, whereas a single percolate water sample was analyzed per replicate mesocosm per sampling date.

Statistical Analyses

A one-way analysis of variance (ANOVA) of water quality parameters for STE as a function of time indicated significant differences on days 98 and 216 of the experiment. As such, values for these dates were excluded from our analysis. Differences among depth treatments were determined at the 95% confidence level using a one-way ANOVA on ranks and Tukey's test for means separation ($P<0.05$).

Results

Ammonium concentration in percolate water declined over the course of the experiment from 25–27 mg N/L to less than 5 mg N/L, with no significant differences observed among depths on any sampling date (Fig. 2). The concentration of nitrate in percolate water increased initially at all depths, with nitrate levels that were significantly different among sand depths after operation for 42 and 70 days (Fig. 2). No significant differences in NO$_3$

levels were observed among depths on any subsequent dates. Medium depth had no significant effect on the pH of percolate water, which declined steadily during the experiment (Fig. 2). Depth did not have a significant effect on pH on any sampling date. Initial values of DO in percolate water ranged from 3.7 to 4.7 mg/L, and DO values increased during the course of the experiment, with final values ranging from 7.3 to 7.5 mg/L (Fig. 2). No significant differences in DO were observed among treatments on any sampling date. Levels of BOD_5 in percolate water decreased in all treatments during the course of the experiment, and no significant differences were observed among depth treatments on any sampling date (Fig. 2). The concentration of PO_4 in percolate water exhibited a great deal of variation during the course of the experiment; however, there were no significant differences among treatments on any sampling date (Fig. 2). We did not observe treatment differences in the concentration of SO_4 in percolate water among treatments and no Fe^{2+} was detected in percolate water from any of the treatments (data not shown).

Removal rates for N varied during the experiment and were not significantly different among treatments on any sampling date (Fig. 3). When averaged over the course of the experiment, N removal rates (s.d.) were 28.0% (8.7), 21.6% (8.0), and 22.5% (8.0) for sand at depths of 7.5, 15, and 30 cm, respectively. Sand depth had no statistically significant effect on the rate of removal of P on any sampling date (Fig. 3). As was the case for N removal, rates of removal for P varied throughout the course of the experiment. Values of P removal averaged over the course of the experiment were 17.5 (8.0), 13.3 (6.8), and 15.5 (6.3) for 7.5, 15 and 30 cm, respectively. The rate of removal for BOD_5 increased over the course of the experiment in all treatments, with no significant differences observed among depths (Fig. 3). Removal rates for BOD_5 averaged over the course of the experiment were 81.4% (9.2), 90.6% (9.3), and 89.0% (7.0) for 7.5, 15, and 30 cm, respectively. Fecal coliform removal rates also varied throughout the course of the experiment, and no significant differences were observed among treatments on any sampling date (Fig. 3). Averaged over the course of the experiment, fecal coliform mean removal rates for 7.5, 15, and 30 cm were 82.4% (17.7), 92.3% (5.6), and 85.7% (9.5), respectively.

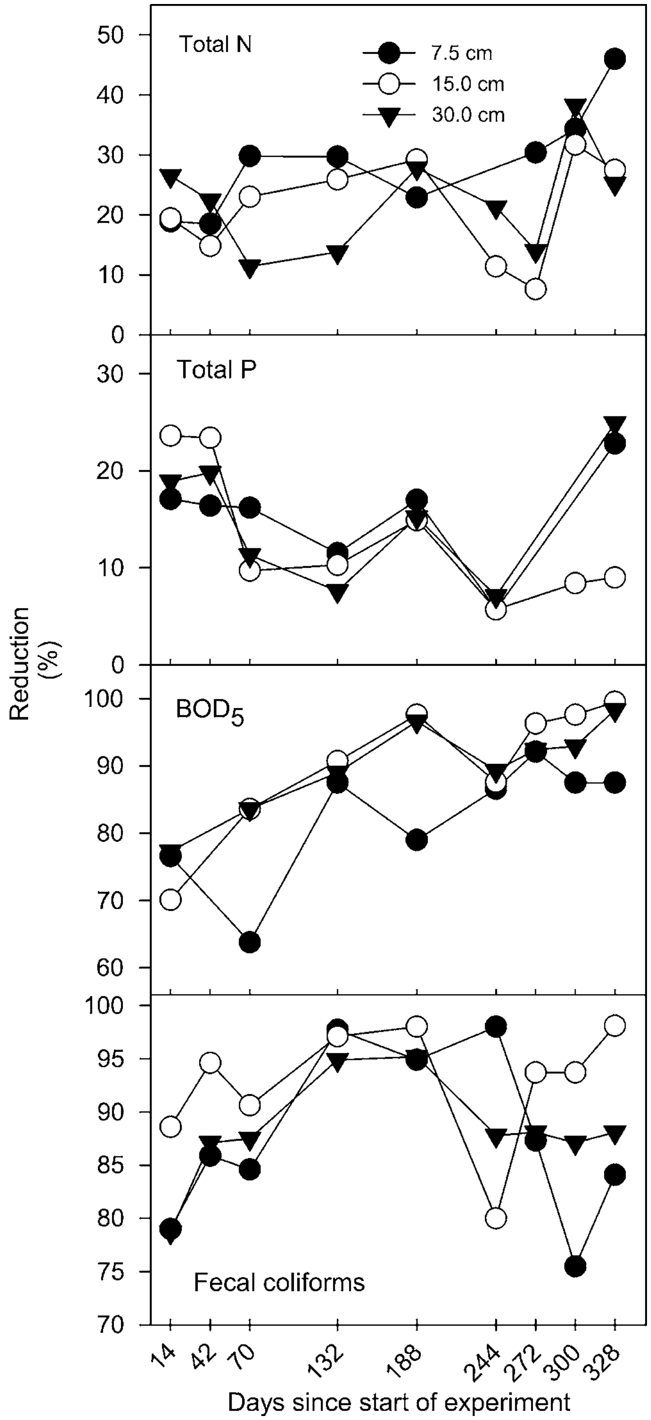

Fig. 3. Removal of fecal coliform bacteria, BOD_5, total P, and total N as a function of time in intermittently aerated mesocosms with different sand depths. Values are means ($n=3$).

Discussion

The time-averaged performance of the intermittently aerated leachfield mesocosms was comparable to that observed by others in terms of removal of N, BOD_5, and fecal coliform bacteria in tests using leachfield porous materials with an equal or greater medium depth than in the present study (Duncan et al. 1994; Harrison et al. 2000; Magdoff et al. 1974; Pell and Nyberg 1989a,b; Rodgers et al. 2004; van Cuyk et al. 2001). Sand depth did not appear to have a significant effect on water quality parameters or contaminant removal rates, regardless of whether differences were evaluated on individual sampling dates or over the course of the experiment. Furthermore, temporal patterns of percolate water quality parameters and removal rates were similar regardless of depth. These results run counter to conventional wisdom with respect to wastewater renovation in porous media, which equates greater depth with increased contaminant removal.

The insensitivity of removal processes for total N and BOD_5 to medium depth—which involve the activities of microorganisms—may result from the establishment of conditions that support the necessary microbial processes in a narrow ($\leq$7.5 cm) area below the infiltrative surface. Foremost among these is the recurring increase in the level of O_2 at the infiltrative surface brought about by intermittent aeration. In the case of BOD_5, the microbial oxidation of organic carbon is more energetically efficient when microorganisms employ O_2 as the terminal electron acceptor (Fuhrmann 2005). Analysis of the structure of the microbial community of intermittently aerated and unaerated sand mesocosms in an experiment similar to the present study (Amador et al. 2006) found a larger active microbial biomass at 0–4 cm than at 4–13 cm in intermittently aerated soil, suggesting that microbial activities are more concentrated in the area immediately below the infiltrative surface. The combination of periodic increases in availability of O_2 and a larger active microbial population near the infiltrative surface may explain the insensitivity of BOD_5 removal to soil depth.

In contrast to our results, Peeples et al. (1991) found that removal rates for BOD_5 in sand filters receiving domestic wastewater increased with depth, with mean values of 53, 69, and 75% reported for depths 30, 45, and 60 cm, respectively. BOD_5 removal rates in the present experiment were consistently higher (Fig. 3) than those reported by Peeples et al. (1991) even at the lowest depth (7.5), suggesting that intermittent aeration may be able to compensate for depth of medium for BOD_5 removal.

Initially total N removal likely involves the buildup of microbial biomass N. However, the intermittent introduction of air also supports microbial oxidation of NH_4 to NO_3, which initially was found to increase with sand depth. This increase may be due to longer fluid retention times in deeper mesocosms, which would expose nitrifying populations to NH_4 for longer periods of time, allowing for faster growth. If we assume the microbial population will reach steady state with respect to N removal for growth, net N removal then requires reduction to N_2O and N_2 by denitrifiers. Insensitivity of N removal to soil depth may stem from the establishment of conditions that promote nitrification and denitrification in the zone immediately below the infiltrative surface at different times. In this conceptual model, nitrification takes place in the porous medium during periods of aeration that alternate with periods of anoxia caused by the introduction of wastewater containing high concentrations of organic carbon substrates into the same zone where NO_3 is produced. Thus, assuming that denitrifying bacteria are present in the wastewater and/or the sand, all of the conditions necessary for N removal by denitrification can be met over a short distance. This mechanism is similar to N removal in wastewater treatment plants using a sequencing batch reactor (Henze et al. 1997), with the nitrification and denitrification steps separated in time.

The main abiotic mechanism of phosphorus removal in leachfield soil is thought to involve sorption and binding of PO_4 with iron and aluminum oxides and oxyhydroxides on the surface of soil particles (Robertson 2003; Zanini et al. 1998). However, as indicated in Potts et al. (2004), the quartz sand employed in our experiments does not contain appreciable amounts of these oxides, making this an unlikely removal mechanism. Straining of particulate P and microbial growth both likely contribute to P removal in our systems. In addition, our results may be explained by the involvement of enhanced biological phosphate removal (EBPR) processes observed in activated sludge. Removal of P in the activated sludge process via EBPR requires alternating aerobic and anaerobic conditions (Mino et al. 1998). Net removal of P in association with EBPR can result from precipitation with Ca^{2+} present in wastewater as long as the pH remains near neutral (Maurer et al. 1999). In the absence of other abiotic removal mechanisms, P removed by EBPR in our sand mesocosms has the potential to migrate below this zone as microorganisms die and biomass P is mineralized. However, the mineralogy of particles in leachfield soils is generally such that abiotic reactions with oxides of aluminum and iron will result (Robertson 2003; Zanini et al. 1998), reducing the potential for migration.

If EBPR is the principal removal mechanism, the lack of P removal in response to sand depth may be explained by the fact that soil immediately below the infiltrative surface can be expected to have the highest concentrations of O_2 during aeration periods as well as the longest periods of anoxia following inputs of wastewater and prior to aeration. Reports of simultaneous removal of N and P from wastewater via denitrification and EBPR in sequencing batch reactors (Gieseke et al. 2002; Zeng et al. 2003) lend support to the notion that both of these processes may have been active in our mesocosms.

Straining is believed to be involved in the removal of fecal coliform bacteria in leachfield soils (Reddy et al. 1981). If this is the case, the absence of a significant effect of soil depth on fecal coliform removal indicates that straining takes place over a relatively short distance. In addition, aeration may promote conditions that are adverse to survival of fecal coliform bacteria in soil below the infiltrative surface. For example, in a previous experiment, we found that soil in the top 4 cm of intermittently aerated lysimeters had significantly larger numbers of bacterivorous nematodes and protozoa—believed to be involved in removal of fecal coliform bacteria—than soil at 4–13 cm (Amador et al. 2006). Development of a biomat that restricts water movement is known to improve fecal coliform removal, especially in coarse media (Stevic et al. 2004). However, the absence of a conventional biomat in intermittently aerated leachfield mesocosms (Potts et al. 2004) did not hinder their ability to remove fecal coliforms, with removal rates >99% observed. Differences between rates reported by Potts et al. (2004) and the more modest removal rates (82 to 91%) observed in the present study may be attributed to differences in the duration of the experiments. The systems in Potts et al. (2004) were run for 24 months versus 11 months in the present study. Longer running times may allow for development of biotic and abiotic conditions that further enhance bacterial removal.

Our results suggest that intermittent aeration of leachfield soil results in renovation of wastewater over a short distance below the infiltrative surface. This has important implications for design and permitting of innovative OWTS technologies. The proposed renovation mechanisms for N and P, involving alternating aerobic and anaerobic conditions, may circumvent the limitations imposed by the regulatory requirement of arbitrary distances between the ground water and the infiltrative surface without affecting the level of wastewater renovation. Intermittently aerated leachfield technology may be of use in soils deemed unsuitable for installation of conventional OWTS because of a shallow water table. Implementation of this technology will likely require reevaluation of land use regulations governing site suitability for treatment and disposal of domestic wastewater in decentralized systems, as has been suggested for other innovative OWTS, such as shallow trench low-pressure pipe systems (Winkler and Feiden 2001).

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