Nutrient removal from septic effluents as affected by soil thickness and texture

A. D. Karathanasis, T. G. Mueller, B. Boone and Y. L. Thompson

ABSTRACT

This study evaluated the effectiveness of soils with different textures and thickness to treat BOD, N and P eluted from household septic effluent. The assessments were accomplished by leaching undisturbed soil monoliths of 30, 45 and 60 cm thickness and 25 cm in diameter, representing the four different textural groups and hydraulic loadings recommended by the Kentucky Health Department, with domestic wastewater effluent collected regularly from a household septic system. Effluent concentrations were monitored daily over a 15 d period for biochemical oxygen demand (BOD), total-N, NH_4–N, NO_3–N and total-P concentrations. The results of the study indicate an alarming frequency of failure to comply with EPA criteria for BOD, total-N and NH_4–N concentrations when using a 30 cm vertical separation distance between the bottom of the drain field and a limiting soil interface. The treatment performance was particularly poor in coarse-textured soils, apparently due to insufficient reactive surface area. Although biomat development over time is expected to improve the treatment for some of these parameters, the high influent levels of BOD pose great concerns for surface and groundwater contamination during the early stages of operation. Fine-textured soils generally provided better treatment efficiency and more consistent compliance with EPA standards for BOD, total-N, NH_4–N and total-P, as well as greater nitrification/denitrification potential. Treatment efficiency and compliance usually improved with increasing soil depth, with the 60 cm thickness providing the most consistent performance and compliance with MDL requirements. Considering that increasing soil thickness requirements may be impractical in many marginal soils, complementary or alternative treatment technologies should be adopted to improve treatment efficiency and prevent further deterioration of the quality of water resources.

Key words | BOD, domestic wastewater treatment, NH_4–N, NO_3–N, soil monoliths, soil thickness, soil texture, total-N, total-P, vertical separation distance

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INTRODUCTION

In many states contamination of surface and groundwaters by fecal bacteria and nutrients originating from failing or inadequately designed septic systems has been a major non-point-source pollution problem (US EPA 2002). As residential development encroaches upon rural areas and increasing population places additional demands on water resources the need for adequately functioning septic systems is becoming more critical. Existing guidelines assume that a minimum of 30 cm of suitable soil material between the bottom of the drain field and limiting soil features, such as bedrock, fragipan, claypan, unsuitable structure or water table, will provide adequate treatment to infiltrating sewage effluents. This vertical distance separation standard has not been experimentally tested in many cases, in spite of the fact that a lot of soils have one or more of these limitations. Most often, we rely on trial and error

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experiments or we adopt criteria developed from experiences of other states, even if they have completely different soils.

It is well known that not all soils are equally suited for waste disposal (Bouma *et al.* 1972). Suitable soils should be reasonably permeable and well aerated (drained) so that oxidation of the organic waste can take place (Starr & Sawhney 1980; Canter & Knox 1985). Ideal soils should not be extremely fine- or extremely coarse-textured. A coarse-textured soil may pass the wastewater through too rapidly for the soluble materials to be decomposed (University of Wisconsin-Madison 1978). In a fine-textured soil, it may be impossible to maintain adequate long-term drainage because suspended solids and biological exudates may clog many soil pores, thus drastically reducing soil permeability and causing system failure (Vinten *et al.* 1983). In soils with limiting layers or interfaces, these requirements are even more critical to the functionality of the septic system. Since the limiting layer itself is unsuitable for treatment, it is very important that the soil below the drain field and above the limiting layer is thick enough and suitable enough in terms of texture and porosity to ensure efficient treatment. If not, sewage effluent will overflow the site, causing system failure (Kaplan 1991).

To ensure unsaturated flow conditions, which encourage aerobic microbiological decomposition and enhance nutrient removal below the drain field, minimum separation distances from the bottom of the drain-field trenches to the limiting layer or groundwater have been adopted in different states, depending on the properties of the soil column (Hall 1990; Duncan *et al.* 1994; Minnesota Pollution Control Agency 2001). The recommended separation distances vary from 30–150 cm (Canter & Knox 1985). According to the US EPA Manual (1980), average soils with no channels or fractures are generally safe if the sewage effluent percolates at least 120 cm through unsaturated, relatively permeable soil. The most recent EPA manual (US EPA 2002) suggests a vertical separation distance range of 30–120 cm for secondary treatment, depending on soil type, site vulnerability and water resource management. Surprisingly, many states, including Kentucky (Kentucky Cabinet for Human Resources 1989) recommend only 30–45 cm of vertical separation distance between the drain-field trench bottom and the limiting or restrictive layers, with 30 cm being the standard most often in use. Recent reports by Coyne *et al.* (1997) demonstrate that fecal bacteria are rapidly transported through unsaturated soil to depths of at least 90 cm by modest infiltration events. Therefore, at least at first glance, the existing criteria appear to be very liberal for the areas with a prevalence of soils with limiting features and may explain the observed numerous failures of septic systems.

Therefore there is a critical need to make a consistent evaluation of the effectiveness of the currently used septic system vertical separation database criteria and to develop a database that will provide the foundation for making the needed adjustments and corrections (Cogger & Carlile 1984; Jenssen & Siegrist 1990). Some states (Florida, N. Carolina, Minnesota) have already completed studies leading to the correction of these problems over the last 10 years (Anderson *et al.* 1994). Many others still continue the trial and error approach. Establishing more efficient vertical distance separation criteria will contribute significantly to the reduction of a major NPS pollution source that continues to impair ground and surface water quality in greater proportions every year.

The main objectives of this study were to evaluate the effects of soil texture and thickness of representative Kentucky soils on the treatment of BOD, N and P eluted from domestic wastewater effluents with the goal of developing a preliminary database from which more realistic and effective vertical separation distance criteria can be established.

MATERIALS AND METHODS

Soils

Ten sites were selected representing suitable soil types with diverse textures and thickness in which new septic systems were to be installed. Two to three soils were selected from each of the four soil-textural groups (Table 1) defined in the Kentucky Health Department onsite regulation manual (Kentucky Cabinet for Human Resources, 1989) and treated with the recommended hydraulic loadings. The four soil groups consist of sand or loamy sand texture (Group I), sandy loam or loam texture (Group II), silt loam, clay loam

Table 1 | Site location, particle size distribution and selected chemical properties of the soils used in the study†

Soil group	Soil	Location	Texture	Sand (%)	Silt (%)	Clay (%)	OM (%)	pH	CEC ($cmol_c$/kg)	BS (%)
1	Yeager 1	Martin Co.	LS	82	11	7	0.6	4.9	2.3	11
	Yeager 2	Magoffin Co.	LS	80	10	10	0.6	4.8	2.5	10
2	Bruno	Estill Co.	SL	59	29	12	3.4	6.2	6.2	50
	Lily	Laurel Co.	L	40	44	16	0.4	4.7	5.4	7
	Pope	Magoffin Co.	SL	58	24	18	0.8	4.8	4.7	14
3	Ashton	Fayette Co.	SiL	7	73	20	2.0	6.2	18.0	18
	Nolin	Fayette Co.	SiL	4	76	20	2.5	5.7	14.9	33
	Shelocta	Magoffin Co.	CL	33	39	28	0.7	5.2	8.5	19
4	Lowell	Fayette Co.	SiC/C	8	40	52	0.3	5.7	19.2	45
	Maury	Fayette Co.	SiC	10	48	42	0.1	6.0	16.5	22

†OM = organic matter; CEC = cation exchange capacity; BS = base saturation.

or silty clay loam texture (Group III) and silty clay, sandy clay or clay texture (Group IV). The soils used in the study, their location, texture and group classification are listed in Table 1. In group I we included two soils classified as Yeager (sandy, mixed, mesic, typic udifluvents) with loamy sand texture sampled from Magoffin and Martin Counties. Group II involved three soils with sandy loam, or loam texture, classified as Pope (coarse loamy, mixed, active, mesic, fluventic dystrudepts), Bruno variant (sandy, mixed, thermic, typic udifluvents) and Lily (fine loamy, siliceous, semiactive, mesic, typic hapludults), which were sampled from Magoffin, Estill and Laurel Counties, respectively. Group III included three soils with silt loam and clay loam or silty clay loam textures, classified as Ashton (fine silty, mixed, active, mesic, mollic hapludalfs), Nolin (fine silty, mixed, active, mesic, dystric fluventic eutrudepts) and Shelocta (fine loamy, mixed, active, mesic, typic hapludults), which were sampled from Fayette and Magoffin Counties. Finally, group IV involved two soils with silty clay texture, classified as Maury (fine, mixed, semiactive, mesic, typic paleudalfs) and Lowell (fine, mixed, active, mesic, typic hapludalfs), which were sampled from Fayette County. Although texture is not the only soil property influencing treatment efficiency, most other parameters expected to have an impact (surface area, sorption capacity, cation-exchange capacity, porosity) are considered an accessory to texture because of their significant interdependence. Because of these synergistic effects sizing and loading criteria for septic systems are based mainly on soil textural considerations.

Collection of soil monoliths

The criteria for selection of a soil for the leaching experiment required a uniform texture and structure adhering to the textural specifications of each soil group to a depth of at least 60 cm and the absence of limiting layers such as fragipans, groundwater, claypans, bedrock, massive or platy structure within that depth. Efforts were made to avoid evident cracks, bio-channels, tree roots, rocks and other inclusions that could alter wastewater flow through the column. Sod, litter and other organic materials were removed from the soil surface prior to excavation. Soil pedestals were excavated and then carved into a cylinder to fit inside a PVC pipe of 25 cm inside diameter and 30, 45 or 60 cm height. The three soil thickness increments were to represent the vertical separation distance between the bottom of the drain field and a limiting soil interface. After the PVC pipe was carefully fitted over the soil pedestal, polyurethane foam (Poly U Foam, Kardol Quality Products, St. Petersburg, FL) was poured into the annulus between the PVC and the soil pedestal to stabilize the soil monolith and prevent through-flow of leachate along the side of the PVC wall. The foam was allowed to cure before the monoliths were severed from the bottom and stored in polyethylene bags to maintain their natural moisture content until ready for the leaching procedure.

Leaching experiments

Prior to leaching with domestic wastewater, the soil monoliths were trimmed flush with the top and bottom of the PVC casing and a 5 cm PVC collar was secured to the top of the column. The monoliths were set up on a leaching stand over funnels, which drained into effluent collection bottles. Before initiating the leaching procedure the monoliths were saturated with de-ionized water by immersing them in tubs over a 48 h period to remove air pockets. A layer of washed river gravel was spread over the top of each column to evenly distribute wastewater over the entire surface area to simulate drain field conditions. The monoliths and effluent collection bottles were sealed with plastic laboratory film. To reproduce anaerobic conditions prevalent in real septic systems, the stock wastewater container, the effluent collection bottles and the top of each monolith were maintained under N_2 gas flow conditions. Primary treated domestic wastewater was collected every 3 d from the distribution box of a home site in Lexington with a "Guzzler" type pump and stored in a carboy container. Based on the hydraulic loading rates of 36.6, 28.5, 20.4 and 15.1 $L/m^2/d$ recommended by the Kentucky Cabinet for Human Resources manual (1989) for soil groups I, II, III and IV, respectively, and the monolith surface areas employed in the study, the estimated flow rates used in the leaching cycles were 45 mL/h for soil group I, 35 mL/ h for soil group II, 20 mL/h for soil group III and 15 mL/h for soil group IV. The wastewater was maintained under constant stirring conditions in the carboy during the entire leaching cycle and was applied to the top of each monolith via three or four Nalgene 890 teflon FEP tubes, 16 mm in diameter, at the respective nominal rate, which was controlled by a peristaltic pump. Influent and effluent samples were collected daily over a 15 d period and analyzed for BOD, total-N, NH_4-N, NO_3-N and total-P.

Analytical characterizations

Effluent samples were collected at the completion of each leaching cycle in clean 1000 mL disinfected containers. The standard 5 d BOD (BOD_5) test was used to assess the reduction in biological oxygen demand. Samples were stored at <4°C for approximately 24 h, then warmed to room temperature before analysis. Duplicate samples of 0.1 and 1.0 mL were pipetted into standard 60 mL BOD bottles and brought up to volume with water buffered with a 1.0 $mL\,L^{-1}$ phosphate buffer solution containing $MgSO_4$, $CaCl_2$ and $FeCl_3$ (APHA, 1992). The dissolved oxygen content was determined at inoculation and after 5 d of incubation at 20°C in a BOD incubator. Dissolved oxygen was measured with an YSI 5000 Dissolved Oxygen Meter equipped with a BOD probe (YSI Inc., Yellow Springs, OH).

Total nitrogen and total phosphorus were determined with a Kjeldhal digestion procedure (APHA 1992). This digestion converts all forms of nitrogen to NH_4^+ and all forms of phosphorus to PO_4^-. Twenty-five mL of unfiltered eluent sample or 5 mL of influent sample was pipetted into Kjeldahl digestion tubes. To these, 4.0 mL of concentrated sulfuric acid (H_2SO_4), 0.9 g of potassium sulfate (K_2SO_4), 2 selenium granules and de-ionized water to a volume of 35 mL were added. Samples were heated for 2 h at 160°C to evaporate water in the samples, then digested for an additional $1\frac{1}{2}$ h at 380°C. After cooling to room temperature, the samples were brought up to 50 mL with de-ionized water and shaken for 15 min to thoroughly mix the samples. Ammonium-N in the Kjeldahl-digested samples was determined by a modification of the Chaney & Marbach (1962) method. Twenty μL aliquots of samples were pipetted into the microplate, then 100 μL each of reagents (a) (1.0% phenol and 0.02% sodium nitro-prusside in de-ionized water) and (b) (0.5% sodium hydroxide and 0.042% sodium hypochlorite in de-ionized water) were added. The microplates were sealed with plastic adhesive covers to prevent contamination with atmospheric NH_4^+ and shaken for 30 min. Ammonium-N concentrations were determined colorimetrically at 630 nm with a Microplate Auto-reader (Biotek Instruments, Winooski, VT). Soluble NH_4-N present in non-digested samples was measured similarly following filtration through a 0.45 μm filter. Total-P on Kjeldahl-digested samples was determined colorimetrically following the procedure of D'Angelo *et al.* (2001).

Nitrate-N was determined with a variation of the Griess reaction on samples passed through a 0.45 μm filter. Nitrate was reduced to NO_2^- using a copperized cadmium wire catalyst (University of Kentucky Agronomy Analytical Laboratory, patent pending). To measure NO_3^- concentrations, 10 μL of sample and 200 μL of ammonia buffer (pH 8.5) were shaken for 45 minutes. Sixty microliters of NEDS reagent (a 50/50 mixture of 0.1% N (1-Napthyl) ethylene-diamine-diHCL in de-ionized water and 1.0% sulfanilamide in 3 M HCl) was added. Samples were shaken for an additional 5 min and then read colorimetrically at 540 nm using a Microplate Auto-reader (Biotek Instruments, Winooski, VT).

Statistical analysis

The Least Significance Difference (LSD) procedure of the Statgraphics Plus version 5.0, testing both the 0.05 ($P < 0.05$) and 0.10 ($P < 0.10$) probability levels, was used to test the statistical differences between and within soil textural groups as a function of soil depth in terms of effluent concentrations and percentage removal efficiencies of BOD, total-N, NH_4-N, NO_3-N, and total-P.

RESULTS AND DISCUSSION

Biological oxygen demand

Influent BOD levels were quite high and variable during the sampling period, ranging from 92 mg/L in group III soils to 1157 mg/L in group II soils. Total average concentrations (Tables 2–5) were highest and most variable in group III soils (~413 mg/L) and lowest with the least variability in group I soils (~294 mg/L). Soil groups II and IV showed intermediate BOD levels (~329 and ~350 mg/L, respectively) and variability between samplings. These averages are slightly higher than the upper range of BOD levels reported as typical for residential wastewater in the literature (US EPA, 2002).

Average effluent BOD concentrations were generally very high, suggesting the inadequacy of the treatment provided regardless of soil group and soil depth (Tables 2–5). They ranged from 12.5 mg/L in the 60 cm monolith of the Maury soil (group IV) to ~335 mg/L in the 45 cm monolith of the Yeager 1 soil (group I). Overall, mean effluent BOD concentrations were highest in group II soils (~236 mg/L) and lowest in group III soils (~160 mg/L), being more than five-fold higher than the EPA recommended 30 mg/L MDL requirement and comparable to untreated septic tank effluents for typical residential wastewaters (US EPA, 2002). These values are also much higher than BOD concentrations measured 60 cm below the drain field of conventional septic systems installed in fine sands or loamy soils (Anderson *et al.* 1994; University of Wisconsin-Madison, 1978). Only one (Maury soil, 60 cm) of the 30 soil monoliths used in the study was in compliance with the EPA criteria (Tables 2–5). Daily monitoring compliance averaged 2% in soil groups I and II, 18% in soil group III and 23% in soil group IV, suggesting a slight improvement in the treatment provided by group III and IV soils (Tables 2–5). Daily monitoring compliance improved slightly with increasing soil depth from 4% in the 30 cm soil monoliths, to 12% in the 45 cm soil monoliths and then to 18% in the 60 cm soil monoliths, indicating a slight advantage for the 60 cm soil thickness threshold in BOD treatment. Comparing BOD effluent levels between soil groups regardless of soil depth, soil groups III and IV provided a statistically significant ($P < 0.05$) better treatment than soil groups I and II, mainly due to their increased reactive surface area (Figure 1). Considering soil depth treatments, the superiority ($P < 0.05$) of group III and IV soils in BOD treatment was only evident in comparison to the 60 cm soil monoliths (Figure 2), with the advantage of using a 60 cm soil thickness being more clear in effluents of the Ashton and Maury soils (Tables 4 and 5). These results are in agreement with the findings of Duncan *et al.* (1994), who reported significant improvement in the treatment of BOD with increasing soil depth in Virginia soils.

The percentage removal efficiencies for BOD showed dramatic fluctuations between and within soil groups, ranging from 0% in the Yeager I soil (45 cm) to ~96% in

Table 2 | Mean values ± 1 SD for the influent and effluent composition of the wastewater applied to the soil monoliths of group I, percentage removal efficiencies for each soil and depth, and percentage daily compliance with EPA recommended criteria†

		Influent		Effluent		Removal efficiency		Daily compliance	
	Depth	BOD	Total-P	BOD	Total-P	BOD	Total-P	BOD	Total-P
Soil	(cm)	(mg/L)		(mg/L)		(%)		(%)	
Yeager 1	30	346.0 ± 143.1	22.7 ± 11.0	295.1 ± 156.8	0.8 ± 0.5	17.4 ± 35.2	96.2 ± 3.3	0	100
	45	346.0 ± 143.1	22.7 ± 11.0	334.9 ± 182.3	0.4 ± 0.2	0.0 ± 34.2	98.3 ± 0.6	0	100
	60	346.0 ± 143.1	22.7 ± 11.0	306.9 ± 199.5	0.9 ± 0.7	12.5 ± 46.7	95.7 ± 4.1	13	86
Yeager 2	30	268.3 ± 41.0	16.3 ± 3.9	125.6 ± 50.4	4.2 ± 4.3	52.6 ± 20.0	76.1 ± 23.5	0	71
	45	268.3 ± 41.0	16.3 ± 3.9	151.7 ± 57.7	1.6 ± 1.1	43.0 ± 23.4	89.8 ± 6.6	0	57
	60	268.3 ± 41.0	16.3 ± 3.9	173.8 ± 68.7	6.5 ± 3.4	33.9 ± 28.2	57.7 ± 18.6	0	14
Mean	30	293.7 ± 89.5	21.0 ± 10.0	200.1 ± 137.8	2.4 ± 3.3	37.1 ± 32.4	86.8 ± 18.7	0	86
	45	293.7 ± 89.5	21.0 ± 10.0	236.2 ± 158.2	1.0 ± 0.9	22.9 ± 35.9	94.3 ± 6.2	0	79
	60	293.7 ± 89.5	21.0 ± 10.0	235.2 ± 156.7	3.5 ± 3.7	24.0 ± 38.6	77.9 ± 23.3	6	50
Overall mean	–	293.7 ± 89.5	21.0 ± 10.0	224.2 ± 150.3	2.3 ± 3.1	27.9 ± 35.9	86.4 ± 18.5	2	71

†MDL for BOD and Total-P = 30 mg/L and 5 mg/L, respectively.

the Maury soil (60 cm) (Tables 2–5). Soil group mean percentage removal efficiencies in soil groups III and IV were nearly two-fold higher (~56%) than in soil groups I and II (~27%) (Tables 2–5). This trend was statistically significant ($P < 0.05$) in all three soil depths (Figure 3). These results raise great concerns about the adequacy of BOD treatment provided by soils regardless of soil texture even at 60 cm soil depth. Even though BOD treatment is expected to improve over time in leach fields due to biomat development, the extremely high effluent BOD levels encountered in this study and the low percentage removal efficiencies indicate a great potential for groundwater contamination, particularly in early stages of the septic system operation. One of the culprits may be the extremely high influent BOD levels, which may be the result of failing or inadequate septic tank treatment, system overloading or excessive colloidal BOD that is very difficult to attenuate. In any case, such high BOD levels may clog the infiltrative surface, especially following the biomat development, and cause surface seepage or sewage backup to occur. While our results suggest that finer-textured soils with increased soil thickness may considerably improve BOD treatment, this improvement may not be enough without supplementary treatment to prevent groundwater contamination. Since filtration and oxidation are the main BOD removal mechanisms, increased soil clay content and thickness should improve treatment as long as the soil does not have extensive macroporosity that could facilitate BOD movement through preferential flow. On the other hand, since the presence of an adequate oxygen supply in the soil is also essential for the aerobic breakdown of BOD components, care should be taken that the subsoil aeration is not limited or restricted by surface soil compaction or inadequate performance and overload of the septic tanks.

Total nitrogen

Influent concentrations for total N ranged from 12 mg/L in soil group II to 300 mg/L in soil group I, with relatively

Table 3 | Mean values ± 1 SD for the influent and effluent composition of the wastewater applied to the soil monoliths of group II, percentage removal efficiencies for each soil and depth, and percentage daily compliance with EPA recommended criteria†

		Influent		Effluent		Removal efficiency		Daily compliance	
	Depth	BOD	Total-P	BOD	Total-P	BOD	Total-P	BOD	Total-P
Soil	(cm)	(mg/L)		(mg/L)		(%)		(%)	
Bruno	30	308.3 ± 162.3	23.0 ± 17.4	236.7 ± 163.2	0.3 ± 0.1	27.4 ± 19.4	97.3 ± 1.8	0	100
	45	308.3 ± 162.3	23.0 ± 17.4	255.8 ± 163.6	0.3 ± 0.1	20.6 ± 22.8	98.2 ± 4.3	0	86
	60	308.3 ± 162.3	23.0 ± 17.4	263.0 ± 176.7	0 ± 0	24.9 ± 28.0	100.0 ± 0	13	100
Lily	30	437.5 ± 260.2	27.5 ± 4.1	328.9 ± 149.8	3.5 ± 3.0	17.8 ± 23.6	88.0 ± 9.1	0	25
	45	437.5 ± 260.2	27.5 ± 4.1	298.0 ± 197.5	0.5 ± 0.7	22.6 ± 27.8	98.2 ± 2.6	0	100
	60	437.5 ± 260.2	27.5 ± 4.1	284.6 ± 117.5	0.2 ± 0.2	24.3 ± 14.2	99.4 ± 0.7	0	100
Pope	30	239.2 ± 68.3	17.6 ± 3.6	159.0 ± 25.7	1.0 ± 1.3	30.4 ± 14.4	94.9 ± 6.3	0	86
	45	239.2 ± 68.3	17.6 ± 3.6	173.8 ± 49.7	6.6 ± 2.7	24.5 ± 21.7	62.7 ± 12.0	0	0
	60	239.2 ± 68.3	17.6 ± 3.6	167.3 ± 64.4	1.0 ± 1.2	29.7 ± 19.2	93.3 ± 8.6	0	71
Mean	30	328.6 ± 197.5	23.3 ± 10.9	280.1 ± 214.0	1.7 ± 2.4	25.1 ± 19.7	92.9 ± 7.7	0	70
	45	328.6 ± 197.5	23.3 ± 10.9	236.9 ± 151.0	2.4 ± 3.3	22.9 ± 23.5	86.4 ± 18.6	0	62
	60	328.6 ± 197.5	23.3 ± 10.9	231.2 ± 126.0	0.4 ± 0.7	26.7 ± 19.6	97.5 ± 5.6	4	91
Overall mean	–	328.6 ± 197.5	23.3 ± 10.9	236.1 ± 137.8	1.5 ± 2.5	24.9 ± 20.9	92.3 ± 12.7	2	74

†MDL for BOD and Total-P = 30 mg/L and 5 mg/L, respectively.

small temporal variability between samplings. Total average concentrations by soil group were not that different, being highest in soil group IV ($\sim$138 mg/L) and lowest in soil group III ($\sim$102 mg/L), with an overall mean of 118 mg/L (Tables 6–9).

Average effluent concentrations were highest overall in soil group I (27.6 mg/L) and lowest in soil group IV (7.8 mg/L), with intermediate levels ($\sim$12 mg/L) for soil groups II and III (Tables 6–9). They ranged from as high as 62.5 mg/L in the 60 cm Yeager 2 soil monolith (group I) to as low as 0 mg/L in the 30 cm Lowell soil monolith (group IV). Only 17 of the 30 soil monoliths used in the study had average total N levels in compliance with the EPA recommended 10 mg/L MDL criteria, including 2 from soil group I, 6 from soil group II, 5 from soil group III and 4 from soil group IV. Of the soil monoliths in compliance with EPA criteria, 5 represented the 30 cm soil depth, 6 the 45 cm soil depth and 6 the 60 cm soil depth. Daily monitoring compliance averaged 34% in soil group I, 70% in soil group II, 71% in soil group III and 76% in soil group IV, indicating a clear improvement in the compliance level with increasing clay content (Tables 6–9). Daily monitoring compliance also improved from 59% in the 30 cm and 45 cm soil monoliths, to 66% in the 60 cm soil monoliths, demonstrating a slight advantage in using the 60 cm soil thickness as the vertical distance separation criterion for total-N compliance in domestic wastewater effluents.

A statistical comparison ($P < 0.05$) of total-N effluent concentrations between soil groups clearly indicates the higher treatment efficiency provided by soil groups II, III,

Table 4 | Mean values ± 1 SD for the influent and effluent composition of the wastewater applied to the soil monoliths of group III, percentage removal efficiencies for each soil and depth, and percentage daily compliance with EPA recommended criteria†

		Influent		**Effluent**		**Removal efficiency**		**Daily compliance**	
	Depth	**BOD**	**Total-P**	**BOD**	**Total-P**	**BOD**	**Total-P**	**BOD**	**Total-P**
Soil	**(cm)**	**(mg/L)**		**(mg/L)**		**(%)**		**(%)**	
Ashton	30	583.3 ± 296.7	37.2 ± 9.0	299.4 ± 228.5	5.1 ± 3.5	55.2 ± 27.4	85.7 ± 9.1	8	14
	45	583.3 ± 296.7	37.2 ± 9.0	224.4 ± 186.4	1.2 ± 1.0	50.3 ± 35.6	96.4 ± 3.3	100	86
	60	583.3 ± 296.7	37.2 ± 9.0	135.2 ± 193.6	1.3 ± 1.2	77.8 ± 26.9	96.1 ± 3.5	31	71
Nolin	30	216.7 ± 91.5	5.9 ± 6.6	103.5 ± 72.5	0.2 ± 0.1	51.1 ± 25.6	91.0 ± 6.1	7	100
	45	216.7 ± 91.5	5.9 ± 6.6	106.6 ± 82.7	0.2 ± 0.1	49.4 ± 29.5	90.5 ± 7.6	7	100
	60	216.7 ± 91.5	5.9 ± 6.6	127.9 ± 87.9	0.3 ± 0.1	41.7 ± 29.0	89.1 ± 7.7	7	100
Shelocta	30	497.9 ± 258.9	8.6 ± 5.5	120.9 ± 74.8	0.7 ± 0.7	72.0 ± 13.4	92.0 ± 4.2	0	86
	45	497.9 ± 258.9	8.6 ± 5.5	159.6 ± 101.3	0.4 ± 0.4	63.7 ± 21.3	93.4 ± 5.1	0	100
	60	497.9 ± 258.9	8.6 ± 5.5	203.7 ± 139.3	2.6 ± 2.1	56.9 ± 20.1	71.4 ± 20.9	0	57
Mean	30	412.6 ± 268.3	21.6 ± 17.0	166.2 ± 158.9	2.8 ± 3.4	59.5 ± 24.0	88.7 ± 8.0	5	67
	45	412.6 ± 268.3	21.6 ± 17.0	160.5 ± 134.2	0.8 ± 0.8	54.4 ± 29.2	94.1 ± 5.5	36	95
	60	412.6 ± 268.3	21.6 ± 17.0	154.9 ± 145.8	1.4 ± 1.6	55.3 ± 29.2	87.9 ± 15.1	13	76
Overall mean	–	412.6 ± 268.3	21.6 ± 17.0	160.4 ± 145.3	1.6 ± 2.4	57.4 ± 27.5	90.2 ± 11.0	18	79

†MDL for BOD and Total-P = 30 mg/L and 5 mg/L, respectively.

and IV over that of soil group I (Figure 4). This trend is much more evident ($P < 0.05$) in the 30 and 60 cm soil monoliths, which showed a smaller overall within-soil-group variability (Figure 5). Percentage removal efficiencies for total-N varied considerably, ranging from 44.3% in the Yeager 2 (60 cm) soil monolith to 100% in the Lowell (30 cm) soil monolith (Tables 6–9). Mean percentage removal efficiencies for total-N increased significantly ($P < 0.05$) from coarse to finer-textured soils, following the sequence: soil group I (~76%) < soil groups II and III (~85–88%) < soil group IV (~95%) (Tables 6–9). However, the advantage of increasing soil thickness from 30 to 60 cm to improve total N percentage removal efficiency was not statistically clear ($P < 0.05$) between soil groups.

In spite of the overall high percentage removal efficiencies for total-N by all soil groups, daily compliance records, especially for soil group I, was <35%, raising great concerns about the poor quality of treatment provided from group I soils, even at the 60 cm soil depth (Tables 6–9). Total-N removal efficiency improved significantly and compliance more than doubled in other soil groups, reaching maximum levels in group IV soils. Fine-textured soils have a larger surface area and greater cation-exchange capacity, which enhance NH_4–N adsorption on particle surfaces, while their small size pores provide a more effective filtration of particulate organic N (Harrison *et al.* 2000). Jenssen & Siegrist (1990) also found that nitrification/denitrification processes are favored in fine-grained soils, particularly in the presence of elevated organic carbon

Table 5 | Mean values ± 1 SD for the influent and effluent composition of the wastewater applied to the soil monoliths of group IV, percentage removal efficiencies for each soil and depth, and percentage daily compliance with EPA recommended criteria†

		Influent		Effluent		Removal efficiency		Daily compliance	
	Depth	BOD	Total-P	BOD	Total-P	BOD	Total-P	BOD	Total-P
Soil	(cm)	(mg/L)		(mg/L)		(%)		(%)	
Lowell	30	364.0 ± 152.0	19.9 ± 4.5	232.4 ± 172.6	0.2 ± 0.1	43.2 ± 23.2	98.8 ± 0.6	0	100
	45	364.0 ± 152.0	19.9 ± 4.5	280.3 ± 176.9	1.3 ± 1.4	28.3 ± 20.1	92.7 ± 9.0	0	71
	60	364.0 ± 152.0	19.9 ± 4.5	259.2 ± 189.6	1.1 ± 0.6	35.9 ± 23.1	94.2 ± 3.2	0	86
Maury	30	346.0 ± 161.5	44.5 ± 16.8	149.2 ± 138.8	3.4 ± 2.9	61.5 ± 25.7	91.9 ± 7.4	20	47
	45	346.0 ± 161.5	44.5 ± 16.8	135.0 ± 137.7	3.3 ± 3.3	66.1 ± 26.6	91.9 ± 8.3	27	60
	60	346.0 ± 161.5	44.5 ± 16.8	12.5 ± 9.8	0.6 ± 0.1	95.9 ± 2.7	98.6 ± 0.6	93	100
Mean	30	349.5 ± 154.0	36.7 ± 18.2	189.3 ± 158.7	2.3 ± 2.8	52.7 ± 25.8	94.3 ± 6.8	10	73
	45	349.5 ± 154.0	36.7 ± 18.2	204.9 ± 171.4	2.7 ± 3.0	47.9 ± 30.2	92.2 ± 8.3	13	66
	60	349.5 ± 154.0	36.7 ± 18.2	131.8 ± 179.7	0.7 ± 0.4	67.0 ± 34.4	97.1 ± 2.8	47	93
Overall mean	–	349.5 ± 154.0	36.7 ± 18.2	175.3 ± 171.0	1.9 ± 2.5	55.9 ± 31.1	94.5 ± 6.7	23	77

†MDL for BOD and Total-P = 30 mg/L and 5 mg/L, respectively.

concentrations. This trend was especially evident at the 30 and 60 cm soil depths. Even though a relatively high level of within-soil group variability somewhat skewed the positive effect of increasing soil depth on total-N removal efficiency, the 60 cm soil thickness yielded the lowest overall effluent concentrations in most soils and the highest percent removal efficiencies (Tables 6–9).

NH_4–Nitrogen

Influent NH_4–N concentrations varied considerably between soil groups and sampling periods, ranging from 1 mg/L in group III soils to 178 mg/L in group II soils. Total average concentrations were highest in group IV soils and lowest in group III soils, with an overall mean and standard deviation of 75 ± 44 mg/L among soil groups (Tables 6–9). Considering the low pH range (4.7–6.2) of the soils studied, this suggests that nearly 3/4 of the total influent N is in the NH_4 form. Average effluent concentrations ranged from 0.1 mg/L in the 45 cm Nolin (group III) soil monolith to 52.4 mg/L in the 60 cm Yeager 2 (group I) soil monolith. Overall, mean effluent concentrations were highest in soil group I monoliths and lowest in soil group III monoliths, with the Yeager 2 soil showing the worst and Nolin soil the best attenuation capacity (Tables 6–9). About 21 of the 30 soil monoliths used in the study had average effluent NH_4-N levels below the 6.4 mg/L limit recommended by EPA for the

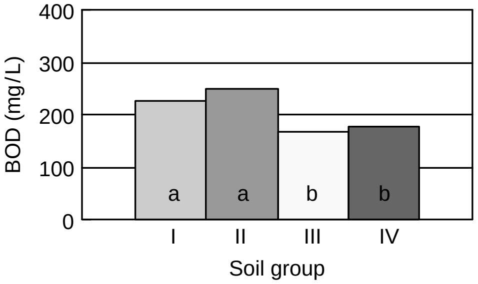

Figure 1 | Statistical comparisons ($a = 0.05$) of mean BOD concentrations eluted from each soil group regardless of soil thickness treatment.

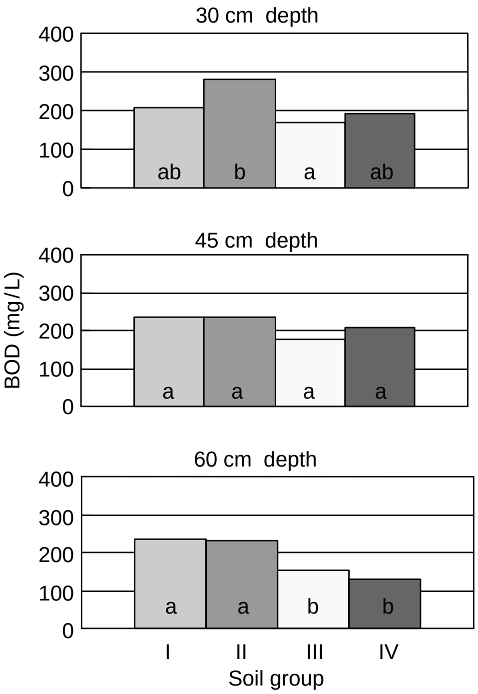

Figure 2 | Statistical comparisons (*a* = 0.05) of mean BOD concentrations eluted from each soil group at 30, 45 and 60 cm soil thickness treatments.

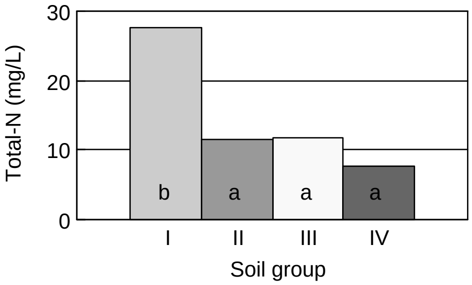

Figure 4 | Statistical comparisons (*a* = 0.05) of mean total-N concentrations eluted from each soil group regardless of soil thickness treatment.

pH and temperature range encountered in the study. Only 2 of these soil monoliths were from soil group I, 6 were from soil group II, 8 from soil group III and 5 from soil group IV. Four of these soil monoliths represented the 30 cm soil depth, 8 the 45 cm soil depth and 9 the 60 cm soil depth treatment. Daily monitoring compliance averaged 55% in group I soil monoliths, 75% in group II soil monoliths and 88% in group III and IV soils, suggesting an improved treatment consistency in finer textured soils (Tables 6–9). Treatment consistency also improved with increasing soil depth from an

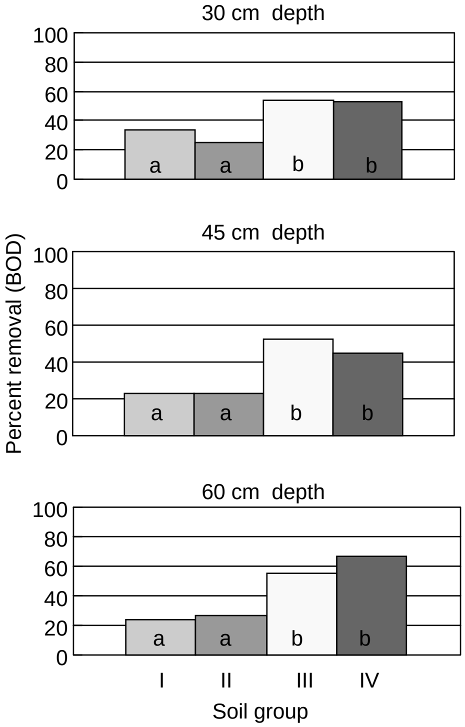

Figure 3 | Statistical comparisons (*a* = 0.05) of mean percentage removal efficiencies for BOD by each soil group at 30, 45 and 60 cm soil thickness treatments.

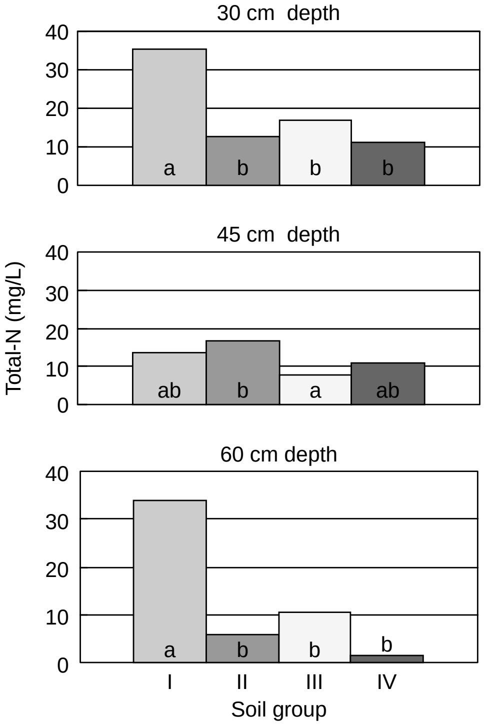

Figure 5 | Statistical comparisons (*a* = 0.05) of mean total-N concentrations eluted from each soil group at 30, 45 and 60 cm soil thickness treatments.

Table 6 | Mean values ± 1 SD for the influent and effluent composition of the wastewater applied to the soil monoliths of group I, percentage removal efficiencies for each soil and depth, and percentage daily compliance with EPA recommended criteria†

		Influent			Effluent			Removal efficiency			Daily compliance		
Soil	Depth (cm)	Total-N (mg/L)	NH_4-N (mg/L)	NO_3-N (mg/L)	Total-N (mg/L)	NH_4-N (mg/L)	NO_3-N (mg/L)	Total-N (%)	NH_4-N (%)	NO_3-N (%)	Total-N (%)	NH_4-N (%)	NO_3-N (%)
Yeager 1	30	109.0 ± 78.5	88.4 ± 42.0	0.1 ± 0.1	27.1 ± 19.4	19.9 ± 17.9	0.2 ± 0.1	73.5 ± 19.8	72.7 ± 23.8	<0	38	43	100
	45	109.0 ± 78.5	88.4 ± 42.0	0.1 ± 0.1	9.8 ± 2.8	4.1 ± 1.2	0.2 ± 0.1	90.7 ± 5.4	94.0 ± 4.3	<0	50	100	100
	60	109.0 ± 78.5	88.4 ± 42.0	0.1 ± 0.1	9.0 ± 1.4	3.6 ± 1.4	0.1 ± 0.1	91.4 ± 4.2	94.5 ± 4.0	49.5 ± 79.9	75	100	100
Yeager 2	30	116.9 ± 58.8	76.9 ± 42.8	0.4 ± 0.2	44.8 ± 45.1	25.6 ± 23.0	0.3 ± 0.1	67.3 ± 19.0	62.5 ± 34.0	<0	14	36	100
	45	116.9 ± 58.8	76.9 ± 42.8	0.4 ± 0.2	17.9 ± 7.9	13.2 ± 9.2	0.1 ± 0.1	82.8 ± 9.3	76.6 ± 25.0	70.1 ± 38.2	29	43	100
	60	116.9 ± 58.8	76.9 ± 42.8	0.4 ± 0.2	62.5 ± 38.2	52.4 ± 39.5	0.1 ± 0.1	44.3 ± 24.9	17.8 ± 74.4	63.4 ± 46.1	0	7	100
Mean	30	125.5 ± 68.1	82.6 ± 42.0	0.2 ± 0.2	35.4 ± 33.8	22.8 ± 20.4	0.3 ± 0.2	70.6 ± 19.0	67.6 ± 29.3	<0	26	39	100
	45	125.5 ± 68.1	82.6 ± 42.0	0.2 ± 0.2	13.6 ± 7.0	8.6 ± 7.9	0.1 ± 0.1	87.0 ± 8.3	85.3 ± 19.7	8.6 ± 86.6	39	72	100
	60	125.5 ± 68.1	82.6 ± 42.0	0.2 ± 0.2	34.0 ± 37.3	28.0 ± 37.0	0.1 ± 0.1	69.4 ± 29.4	56.2 ± 64.8	56.4 ± 64.4	38	54	100
Overall mean	–	125.5 ± 68.1	82.6 ± 42.0	0.2 ± 0.2	27.6 ± 30.4	19.8 ± 25.9	0.2 ± 0.2	75.7 ± 21.9	69.7 ± 43.8	0.1 ± 103.5	34	55	100

†MDL for Total-N, NH_4-N, and NO_3-N = 10 mg/L.

Table 7 | Mean values ± 1 SD for the influent and effluent composition of the wastewater applied to the soil monoliths of group II, percentage removal efficiencies for each soil and depth, and percentage daily compliance with EPA recommended criteria†

		Influent			Effluent			Removal efficiency			Daily compliance		
	Depth	Total-N	NH_4-N	NO_3-N	Total-N	NH_4-N	NO_3-N	Total-N	NH_4-N	NO_3-N	Total-N	NH_4-N	NO_3-N
Soil	(cm)		(mg/L)			(mg/L)			(%)			(%)	
Bruno	30	107.7 ± 85.3	74.0 ± 64.7	0.1 ± 0.1	0.2 ± 0.3	3.6 ± 3.9	6.8 ± 5.8	99.6 ± 0.7	88.9 ± 15.4	<0	100	86	64
	45	107.7 ± 85.3	74.0 ± 64.7	0.1 ± 0.1	4.9 ± 1.9	5.9 ± 6.7	1.7 ± 2.4	86.6 ± 15.2	92.7 ± 4.4	<0	100	64	100
	60	107.7 ± 85.3	74.0 ± 64.7	0.1 ± 0.1	1.1 ± 0.9	1.7 ± 2.2	3.4 ± 2.1	98.7 ± 0.9	98.0 ± 1.5	<0	100	100	100
Lily	30	125.0 ± 45.3	96.7 ± 43.4	0.1 ± 0.1	27.2 ± 20.8	23.1 ± 8.1	0.1 ± 0.1	79.6 ± 11.3	55.8 ± 54.9	<0	25	0	100
	45	125.0 ± 45.3	96.7 ± 43.4	0.1 ± 0.1	3.2 ± 3.7	6.1 ± 2.6	0.1 ± 0.1	97.0 ± 3.1	80.0 ± 36.2	<0	88	87	100
	60	125.0 ± 45.3	96.7 ± 43.4	0.1 ± 0.1	1.6 ± 0.6	2.5 ± 0.8	0.2 ± 0.2	98.0 ± 2.5	92.8 ± 12.6	<0	100	100	100
Pope	30	102.4 ± 19.6	63.4 ± 20.0	0.1 ± 0.1	8.9 ± 6.7	6.5 ± 3.7	0.1 ± 0.1	90.0 ± 7.8	89.0 ± 6.1	<0	71	86	100
	45	102.4 ± 19.6	63.4 ± 20.0	0.1 ± 0.1	41.7 ± 14.7	14.9 ± 13.6	1.9 ± 1.3	57.8 ± 12.6	77.8 ± 16.0	<0	0	50	100
	60	102.4 ± 19.6	63.4 ± 20.0	0.1 ± 0.1	15.0 ± 10.4	2.4 ± 2.9	18.9 ± 19.9	83.0 ± 14.1	94.5 ± 7.9	<0	43	100	50
Mean	30	113.1 ± 54.6	78.5 ± 47.4	0.1 ± 0.1	12.8 ± 17.2	11.0 ± 10.3	2.3 ± 4.6	88.8 ± 11.5	77.9 ± 36.0	<0	66	57	88
	45	113.1 ± 54.6	78.5 ± 47.4	0.1 ± 0.1	16.5 ± 20.1	9.0 ± 9.7	1.3 ± 1.7	81.0 ± 20.2	83.5 ± 23.4	<0	63	67	100
	60	113.1 ± 54.6	78.5 ± 47.4	0.1 ± 0.1	5.7 ± 8.6	2.2 ± 2.1	7.5 ± 13.9	93.2 ± 10.8	95.1 ± 8.7	<0	81	100	83
Overall mean	–	113.1 ± 54.6	78.5 ± 47.4	0.1 ± 0.1	11.6 ± 16.3	7.4 ± 9.0	3.7 ± 8.9	87.7 ± 15.4	85.5 ± 26.1	<0	70	75	90

†MDL for Total-N, NH_4-N, and NO_3-N = 10 mg/L.

Table 8 | Mean values ± 1 SD for the influent and effluent composition of the wastewater applied to the soil monoliths of group III, percentage removal efficiencies for each soil and depth, and percentage daily compliance with EPA recommended criteria†

		Influent			**Effluent**			**Removal efficiency**			**Daily compliance**		
Soil	**Depth (cm)**	**Total-N (mg/L)**	**NH_4-N (mg/L)**	**NO_3-N (mg/L)**	**Total-N (mg/L)**	**NH_4-N (mg/L)**	**NO_3-N (mg/L)**	**Total-N (%)**	**NH_4-N (%)**	**NO_3-N (%)**	**Total-N (%)**	**NH_4-N (%)**	**NO_3-N (%)**
Ashton	30	160.4 ± 48.8	104.3 ± 21.1	0.1 ± 0.1	30.8 ± 20.0	15.5 ± 10.3	3.1 ± 3.9	79.9 ± 11.6	84.5 ± 8.3	<0	14	43	86
	45	160.4 ± 48.8	104.3 ± 21.1	0.1 ± 0.1	11.9 ± 5.2	5.0 ± 4.0	5.7 ± 6.4	91.6 ± 4.1	94.5 ± 4.3	<0	43	86	86
	60	160.4 ± 48.8	104.3 ± 21.1	0.1 ± 0.1	6.5 ± 5.1	2.9 ± 4.0	6.0 ± 3.7	95.6 ± 3.5	97.1 ± 4.4	<0	86	93	93
Nolin	30	44.3 ± 38.5	32.1 ± 34.7	0.1 ± 0.1	2.2 ± 0.6	0.2 ± 0.1	16.0 ± 12.6	92.5 ± 4.2	96.0 ± 6.9	<0	100	100	50
	45	44.3 ± 38.5	32.1 ± 34.7	0.1 ± 0.1	4.7 ± 2.2	0.1 ± 0.1	28.8 ± 21.6	85.4 ± 9.1	98.7 ± 3.1	<0	100	100	21
	60	44.3 ± 38.5	32.1 ± 34.7	0.1 ± 0.1	14.6 ± 6.3	0.5 ± 0.2	50.2 ± 20.9	52.8 ± 31.1	88.0 ± 21.1	<0	7	100	0
Shelocta	30	49.4 ± 21.6	35.3 ± 18.6	0.3 ± 0.1	4.0 ± 2.9	2.2 ± 2.7	0.2 ± 0.1	88.0 ± 9.5	95.1 ± 4.2	37.3 ± 32.2	86	100	100
	45	49.4 ± 21.6	35.3 ± 18.6	0.3 ± 0.1	3.0 ± 2.3	0.7 ± 1.0	0.1 ± 0.1	92.2 ± 6.2	97.5 ± 3.5	71.3 ± 12.6	100	100	100
	60	49.4 ± 21.6	35.3 ± 18.6	0.3 ± 0.1	13.9 ± 7.5	6.2 ± 7.2	0.1 ± 0.1	71.3 ± 12.9	85.0 ± 15.0	66.1 ± 17.2	43	71	100
Mean	30	101.6 ± 69.9	56.1 ± 41.8	0.2 ± 0.1	16.9 ± 19.8	6.0 ± 9.1	6.4 ± 10.2	85.2 ± 11.0	92.0 ± 8.3	<0	67	81	79
	45	101.6 ± 69.9	56.1 ± 41.8	0.2 ± 0.1	7.8 ± 5.7	1.9 ± 3.2	11.5 ± 17.8	90.1 ± 6.7	96.9 ± 4.0	<0	81	95	69
	60	101.6 ± 69.9	56.1 ± 41.8	0.2 ± 0.1	10.4 ± 7.1	3.2 ± 5.2	18.8 ± 25.6	78.2 ± 24.6	89.9 ± 15.8	<0	45	88	64
Overall mean	–	101.6 ± 69.9	56.1 ± 41.8	0.2 ± 0.1	11.7 ± 13.0	3.7 ± 6.5	12.2 ± 19.5	84.5 ± 17.0	92.9 ± 10.9	<0	71	88	71

†MDL for Total-N, NH_4-N, and NO_3-N = 10 mg/L.

Table 9 | Mean values ± 1 SD for the influent and effluent composition of the wastewater applied to the soil monoliths of group IV, percentage removal efficiencies for each soil and depth, and percentage daily compliance with EPA recommended criteria†

		Influent			**Effluent**			**Removal efficiency**			**Daily compliance**		
	Depth	**Total-N**	**NH_4-N**	**NO_3-N**	**Total-N**	**NH_4-N**	**NO_3-N**	**Total-N**	**NH_4-N**	**NO_3-N**	**Total-N**	**NH_4-N**	**NO_3-N**
Soil	**(cm)**		**(mg/L)**			**(mg/L)**			**(%)**			**(%)**	
Lowell	30	80.7 ± 8.2	67.3 ± 8.9	0.1 ± 0.1	0.0 ± 0.0	3.6 ± 1.4	0.1 ± 0.1	100.0 ± 0	94.5 ± 2.6	<0	100	100	100
	45	80.7 ± 8.2	67.3 ± 8.9	0.1 ± 0.1	4.1 ± 6.6	2.7 ± 2.8	0.1 ± 0.1	94.4 ± 9.0	95.6 ± 4.9	<0	36	100	100
	60	80.7 ± 8.2	67.3 ± 8.9	0.1 ± 0.1	1.6 ± 1.6	2.5 ± 1.6	0.1 ± 0.1	97.9 ± 2.2	96.1 ± 2.6	<0	100	100	100
Maury	30	165.3 ± 43.2	110.8 ± 36.3	0.1 ± 0.1	16.6 ± 19.3	11.8 ± 9.4	1.4 ± 0.6	90.3 ± 11.0	88.8 ± 9.0	<0	53	53	100
	45	165.3 ± 43.2	110.8 ± 36.3	0.1 ± 0.1	14.0 ± 17.0	6.3 ± 5.3	9.4 ± 3.0	91.5 ± 9.7	93.6 ± 5.5	<0	67	73	60
	60	165.3 ± 43.2	110.8 ± 36.3	0.1 ± 0.1	1.4 ± 0.5	2.0 ± 1.2	5.0 ± 2.6	99.1 ± 0.5	98.1 ± 1.4	<0	100	100	100
Mean	30	138.4 ± 53.7	89.8 ± 34.4	0.1 ± 0.1	11.1 ± 17.5	7.7 ± 7.8	0.8 ± 0.8	93.6 ± 10.0	91.7 ± 7.1	<0	77	77	100
	45	138.4 ± 53.7	89.8 ± 34.4	0.1 ± 0.1	10.8 ± 14.9	4.5 ± 4.6	4.7 ± 5.3	92.5 ± 9.4	94.6 ± 5.2	<0	51	87	80
	60	138.4 ± 53.7	89.8 ± 34.4	0.1 ± 0.1	1.5 ± 1.0	2.2 ± 1.4	2.7 ± 3.1	98.7 ± 1.4	97.1 ± 2.3	<0	100	100	100
Overall mean	–	138.4 ± 53.7	89.8 ± 34.4	0.1 ± 0.1	7.8 ± 13.8	4.8 ± 5.7	2.7 ± 3.9	94.9 ± 8.3	94.4 ± 5.6	<0	76	88	93

†MDL for Total-N, NH_4-N, and NO_3-N = 10 mg/L.

average daily monitoring compliance of 63% in 30 cm soil monoliths, to 80% and 86% in 45 and 60 cm soil monoliths, respectively. This trend suggests adsorption as a major mechanism for NH_4-N retention in the soil monoliths, since finer-textured soils and greater soil depths provide larger surface area and, therefore, greater adsorption capacity (Sikora and Corey 1976). However, the increased NO_3–N effluent levels compared to influent values in most soil monoliths also support active nitrification processes within the soil matrix of even some coarse-textured soils (Walker *et al.* 1973).

Statistical comparisons ($P < 0.05$) of NH_4–N effluent concentrations between soil groups, regardless of soil depth treatments, showed that soil group II provided more than twice as good NH_4–N attenuation than soil group I, while treatment efficiency in soil groups III and IV was up to 4 times better (Tables 6–9). The superiority of fine textured soils in NH_4–N removal ($P < 0.05$) was evident in all soil depths, but especially at the 60 cm soil depth, where treatment efficiency in soil groups II, III and IV was more than 10-fold higher than in soil group I (Figure 6). These trends were very clear and consistent in spite of considerable treatment variability even within soil groups. Cogger & Carlile (1984) also found significantly lower levels and traveling distances for NH_4–N in septic effluents infiltrating clay, clay loam and sandy clay loam soils than sand and loamy sand soils in North Carolina.

Percentage removal efficiencies of NH_4–N ranged from as low as 17.8% in the 60 cm monolith of Yeager 2 soil (group I) to as high as 98.7% in the 45 cm monolith of the Nolin soil (group III) (Tables 6–9). Soil group mean percentage removal efficiencies varied from ~70% in soil group I to ~94% in soil group IV, with significant statistical differences ($P < 0.05$) between soil groups (Tables 6–9). These differences were apparent at all soil depths, but especially evident at the 60 cm soil depth, where soil groups II, III and IV outperformed ($P < 0.05$) soil group I by a greater than 2:1 ratio (Figure 7). Significant improvement in the treatment of NH_4–N with increasing soil depth has also been reported in soil monolith experiments in Virginia (Duncan *et al.* 1994).

NO_3–Nitrogen

Influent NO_3–N concentrations were very low, indicating the highly anoxic status of domestic wastewater. Total mean

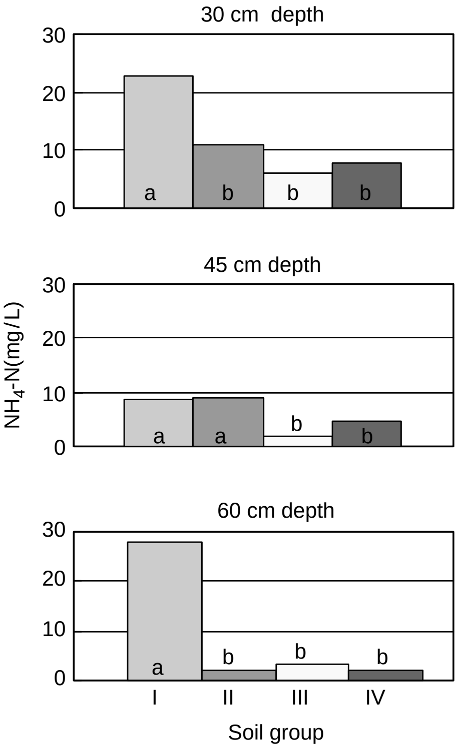

Figure 6 | Statistical comparisons ($a = 0.05$) of mean NH_4–N concentrations eluted from each soil group at 30, 45 and 60 cm soil thickness treatments.

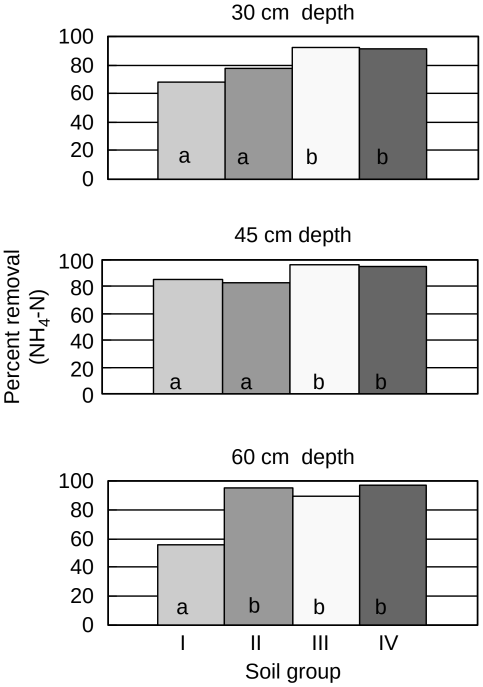

Figure 7 | Statistical comparisons ($a = 0.05$) of mean percentage removal efficiencies for NH_4–N by each soil group at 30, 45 and 60 cm soil thickness treatments.

concentrations ranged from 0.1–0.2 mg/L, with relatively small variability between soil groups and samplings. Effluent NO_3-N levels were much higher, suggesting significant nitrification occurring within the soil monoliths during the leaching process. They ranged from 0.1 mg/L to 50.2 in the 60 cm monolith of the Nolin soil (group III) (Tables 6–9). Mean effluent NO_3-N concentrations were highest overall in soil group III (12.2 mg/L), being especially high in the Nolin soil monoliths, and lowest (0.2 mg/L) in soil group I. Only 4 of the 30 soil monoliths used in the study did not meet the 10 mg/L MDL requirement recommended by EPA. Three of those monoliths were from the Nolin soil (group III) and one (60 cm) from the Pope soil (group II). Apparently, some of the soil monoliths, including the above four, contained a significant number of nitrifying bacteria which were able to convert ample amounts of NH_4-N to NO_3-N in a relatively short time. Since the Nolin soil occupied a depressional landscape position, a certain amount of the NO_3-N present in the soil may have been accumulated as a result of surface runoff and subsurface leaching from adjacent upslope positions. However, residual NO_3-N determinations of this soil indicated concentrations within the range found in other soils used in the study, thus corroborating the presence of greater populations of nitrifying bacteria. This explanation is also supported by the generally higher NO_3-N concentrations present in the effluents of the finer-textured soils compared to those found in soil group I effluents (Tables 6–9). According to Andreoli *et al.* (1979), considerable nitrification occurs in fine-textured soils within 60–120 cm below the drain field. Fine-textured soils usually have a greater surface area for microbial attachment and therefore are more conducive to bacteria proliferation and higher nitrification potential. Another explanation may be the high organic matter content of the Nolin soil (Table 1), which is conducive to higher nitrification rates. Organic carbon can be used as a food source for autotrophic nitrifying bacteria to convert NH_4-N to NO_2-N and eventually to NO_3-N (Jenssen & Siegrist 1990).

Daily monitoring compliance averaged 100% in soil group I, 90% in soil group II, 71% in soil group III (mainly because of the Nolin soil) and 93% in soil group IV (Tables 6–9). Daily monitoring compliance decreased slightly from 92% in the 30 cm soil monoliths to 87% in the 45 and 60 cm soil monoliths probably because of the increased soil surface area and nitrifying bacteria populations present in the deeper soil monoliths. Statistical comparisons of effluent NO_3-N concentrations indicated significantly lower ($P < 0.05$) levels in group I soil monoliths compared to those observed in monoliths of soil groups II, III and IV (Tables 6–9), with significant increases ($P < 0.05$) in effluent concentrations with increasing depth. These results are consistent with the findings of Duncan *et al.* (1994), which reported increases in NO_3-N concentrations with increasing depth for variable influent wastewater compositions.

Because of the higher overall effluent than influent NO_3-N concentrations in most soil monoliths, percentage removal efficiencies were mostly negative (Tables 6–9). However, some soils did have positive NO_3-N removals, ranging from 37% to 71%, including the 60 cm soil monolith of Yeager 1 (group I), the 45 and 60 cm soil monoliths of Yeager 2 (group I) and the three monoliths of the Shelocta soil (group III). The high NO_3-N levels of the Nolin soil (group III) skewed considerably the differences in percentage removal efficiencies between soil groups and made the statistical comparisons meaningless.

Total phosphorus

Influent concentrations for total-P ranged from 1.0 mg/L in soil group I to 71.2 mg/L in soil group IV. Soil group IV also had the highest mean concentration for total-P (36.7 mg/L), while the other soil groups averaged between 21.0 and 23.3 mg/L (Tables 2–5), with relatively small temporal variability. Average effluent concentrations ranged from 0 mg/L in the 60 cm monolith of the Bruno soil (group II) to 6.6 mg/L in the 45 cm monolith of the Pope soil (group II) (Tables 2–5). Mean effluent concentrations were highest overall in group I soils (2.3 mg/L) and lowest in group II soils (1.5 mg/L). Only 2 of the 30 soil monoliths used in the study had effluent total-P levels exceeding 5 mg/L, representing group I and II soils. While total-P MDL criteria have not been established yet, the 5 and 2 mg/L thresholds are being considered as possibilities. Daily monitoring compliance for the 5 mg/L threshold averaged from 80% in soil group I to 95% in soil groups III and IV (Tables 2–5). However, statistical comparisons ($P < 0.05$) of effluent total-P concentrations between soil groups did not indicate significant differences except for the 60 cm soil depth, at which soil group I showed considerable inferiority ($P < 0.05$) for total-P attenuation (Figure 8). This is consistent with the findings of Harman *et al.* (1996), which found extensive phosphate plumes from septic system effluents in sandy soils, in spite of considerable attenuation in the unsaturated zone.

Percentage removal efficiencies for total-P ranged from ~58% in the 60 cm monolith of the Yeager 2 soil (group I) to 100% in the 60 cm monolith of the Bruno soil (group II) (Tables 2–5). The highest overall average percentage removal efficiency was observed in group IV soil monoliths (94.5%), followed by soil groups II (92.3%), III (90.2%) and I (86.4%). These differences, however, were statistically significant ($P < 0.10$) only between group I and group IV soils, without consistent trends with increasing soil depth. Apparently, the superiority of group IV soils for total-P retention stems from their high clay content, which renders a better filtration capacity for particulate organic P, while providing a larger surface area and a greater P-sorption capacity to the soil matrix. Since sorption is the main mechanism for total-P attenuation at soluble levels <5 mg/L, fine-textured soils without macropores are expected to provide a more efficient total-P treatment than coarse textured soils (Sikora & Corey 1976). At higher P levels, another active total-P removal mechanism may be precipitation with iron and aluminum hydroxides, which should be present in the soils studied considering their low pH levels (Table 1). For the same pH level these hydroxides are more abundant in fine-textured soils because they tend to associate more with the clay size particles (Tofflemire & Chen 1977). Therefore, for soils with relatively low to moderate clay content, increasing the required soil vertical separation distance could expand the soil surface area sufficiently to compensate for the inherent inferiority of the soil material.

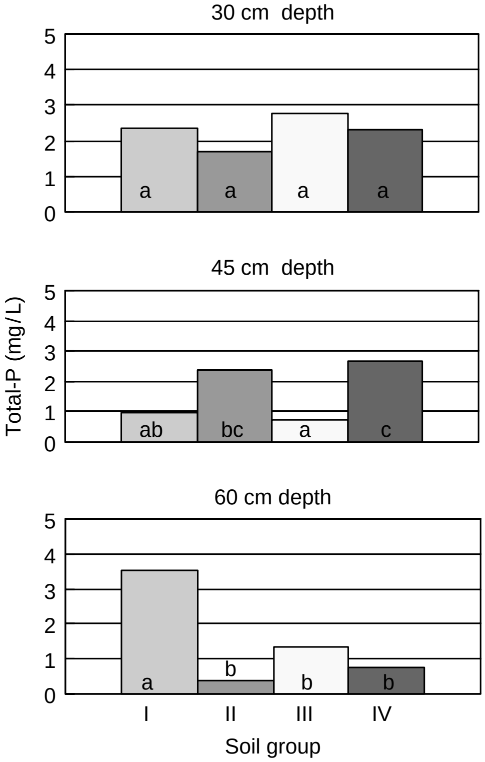

Figure 8 | Statistical comparisons ($a = 0.05$) of mean total-P concentrations eluted from each soil group at 30, 45 and 60 cm soil thickness treatments.

SUMMARY AND CONCLUSIONS

Average influent and effluent BOD levels were very high, suggesting inadequate primary and secondary treatment. Mean percent removal efficiencies and daily compliance were low, particularly in coarse-textured soils. Soil monoliths from groups III and IV showed significantly higher treatment efficiency than soil groups I and II, as documented by lower effluent BOD concentrations and greater percentage removal efficiencies. These differences were more consistent at the 60 cm soil depth. Percentage daily compliance with EPA criteria (30 mg/L) improved with increasing clay content from soil group I through IV, and with increasing soil depth.

Total-N removal efficiency and daily compliance (10 mg/L) improved gradually with increasing clay content, showing the superiority of fine-textured over coarse-textured soils for N treatment. This superiority was more evident at the 60 cm soil depth, probably due to the added soil surface area for filtration and microbial attachment. Attenuation of NH_4–N in fine-textured soils was 2–4 times greater than in coarse-textured soils. This superiority was evident at all soil depths, but especially at the 60 cm soil depth, where treatment efficiency was up to 10-fold higher. Percent daily compliance also increased with clay content, reaching maxima at the 60 cm soil depth in all soils. Influent NO_3-N levels were very low (<0.5 mg/L), suggesting the dominant forms of N in the domestic wastewater to be organic and NH_4-N. Effluent NO_3-N were generally higher than influent concentrations (<0 removal efficiencies), indicating active nitrification/denitrification processes within the soil monolith matrix. Fine-textured soils showed higher nitrification potential, apparently due to their higher surface area for microbial attachment. This is supported by the inverse relationship between percentage daily compliance (10 mg/L) and soil depth, suggesting greater proliferation of bacteria and enhanced nitrification/denitrification with increasing soil surface area. Effluent total-P levels were generally low (<6.6 mg/L), with no significant differences between soil groups, except for the 60 cm soil depth at which fine-textured soils showed considerable treatment superiority over coarse-textured soils. Approximately 80% of the soil group I effluents were below 5 mg/L total-P compared to $>95\%$ of soil group III and IV effluents. These trends demonstrate the inferiority of coarse-textured soils for total-P treatment, due to their limited surface area.

Generally, the majority of the soil monoliths studied provided inadequate nutrient removal efficiency and daily compliance of the septic effluents. Biomat development is expected to improve treatment, but the high influent BOD levels pose great short-term concerns for surface and groundwater contamination, considering that it takes 1–2 years for effective biomat establishment. But, even after that, excessive BOD loadings may quickly lead into drastic reductions in soil permeability, thus causing system failure. The results of this study indicate a gradual, but consistent, improvement in treatment efficiency and EPA compliance with increasing clay content (soil group I → soil group IV) and soil depth (30 → 60 cm). Fine-textured soils generally provided better treatment efficiency, more consistent compliance with EPA criteria for BOD, total-N, NH_4-N and total-P, and greater nitrification/denitrification potential. For most soils the 60 cm soil depth consistently outperformed shallower depths and it was the only soil depth that consistently met MDL requirements. This is strong evidence for increasing the current indiscriminant use of the 30 cm minimum vertical soil separation distance, particularly in coarser-textured soils. Considering that such an increase will reduce even further the number of suitable soil sites in some areas, alternative or complementary treatment technologies should be encouraged in soils with shallower suitable soil depths between the drain-field bottom and the restrictive interface or water table. Constructed wetlands, recirculating sand filters, peat or drip-irrigation systems are among a few complementary or alternative technologies that have been used successfully in other states as substitutes for the lack of a sufficient suitable soil depth.

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