# Effect of soil depth and texture on fecal bacteria removal from septic effluents

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

## ABSTRACT

This study evaluated the effectiveness of soils with different texture and depth to treat fecal bacteria eluted from a house-hold 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 house-hold septic system. Eluent concentrations were monitored daily over a 15 day period for fecal coliform and fecal streptococci concentrations. The results of the study indicate an alarming frequency of failure to comply with United States Environmental Protection Agency (USEPA) criteria for depth to groundwater, when using a 30 cm vertical separation distance between the bottom of the drain-field and a limiting soil interface. The treatment performance was especially poor in coarse-textured soils. Although biomat development over time is expected to improve treatment, the high influent levels of fecal bacteria pose great concerns for surface and groundwater contamination. Fine-textured soils generally provided better treatment efficiency and more consistent compliance with EPA standards. Treatment efficiency and compliance usually improved with increasing soil depth, with the 60 cm thickness providing the most consistent performance and compliance with maximum discharge limit (MDL) requirements. The findings of this study document a general inadequacy of the 30 cm vertical separation distance to provide effective treatment of septic effluents in Kentucky soils, particularly in coarse-textured soils. Considering that increasing the soil depth thickness 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** | domestic wastewater treatment, fecal bacteria, soil monoliths, soil texture, soil thickness, vertical separation distance

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## INTRODUCTION

In many states contamination of surface and ground waters by fecal bacteria and nutrients originating from failing or inadequately designed septic systems has been a major non-point source (NPS) 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 spite of the fact that many soils have one or more of these limitations. Most often we rely on trial and error

doi: 10.2166/wh.2006.043

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 (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. 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 assure efficient treatment. If not, sewage effluent will overflow the site, causing system failure (Kaplan 1991).

To assure unsaturated flow conditions, which encourage aerobic microbiological decomposition and enhance filtration of pathogens 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 (Duncan *et al.* 1994; Harrison *et al.* 2000). The recommended separation distances vary from 60 to 150 cm (Canter & Knox, 1985). According to the US-EPA Manuals (1980; 2002), average soils with no channels or fractures are generally safe if the sewage effluent percolates at least 120 cm through unsaturated, relatively permeable soil. 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 limiting or restrictive layers, with 30 cm being the standard in use most often. Recent reports by Coyne *et al.* (1996, 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 in 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 fecal bacteria 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 texture 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, 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

**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; LS = loamy sand; SL = sandy loam; L = loam; SiL = silt loam; CL = clay loam; SiC = silty clay; C = clay.

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.

## 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 deionized water by immersing them in tubs over a 48- hour 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 days from the distribution box of a home-site (family of 4) in Lexington with a "Guzzler" type pump (Bosworth Company, East Providence, RI) and stored in a carboy container. Based on the hydraulic loading rates of 36.6, 28.5, 20.4, and 15.1 l/m$^2$/day recommended by the Kentucky Health Department onsite regulation 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/hour for soil group I, 35 ml/ hour for soil group II, 20 ml/hour for soil group III, and 15 ml/hour 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 3–4 Nalgene 890 teflon FEP tubes, 16 mm in diameter at the respective nominal rate, which was controlled by a peristaltic pump. Influent and eluent samples were collected daily (every 24 hours) over a 15-day period and analyzed for fecal coliforms and fecal streptococci.

### Analytical characterizations

Effluent samples were collected at the completion of each leaching cycle in clean 1000-ml containers that had been disinfected with bleach (sodium-hypochlorite) to insure that no fecal bacteria were present. The excess bleach in the containers was neutralized with Na-thiosulfate. A 100-ml sub-sample was plated immediately to enumerate fecal bacteria. Fecal bacteria were analyzed by the membrane filtration technique (APHA 1992), using sterile and gridded 0.2-μm pore-size Millipore filters. Multiple sample volumes of 0.1, 1.0, 5.0 or 10.0-ml were plated to increase the probability of obtaining counts within acceptable ranges. Membrane cultures were incubated on M-FC agar (DIFCO, Detroit, MI) for 22 hours at 44.5 °C to enumerate fecal coliform colonies and incubated on K-FS agar (DIFCO) for 48 h at 35°C to assess fecal streptococci.

### 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 statistical differences between and within soil textural groups as a function of soil depth in terms of effluent concentrations and % removal efficiency of fecal bacteria.

## RESULTS AND DISCUSSION

### Fecal coliforms

Fecal coliform (FC) concentrations in the influent were highly variable between soil group treatments and sampling periods, providing a realistic measure of temporal fluctuation to be expected with on-site domestic wastewater treating systems. They ranged from as high as $279.5 \times 10^4$ CFU/100 ml in group III and IV soils to as low as $3.5 \times 10^3$ CFU/100 ml in group III soils. Total average concentrations were highest overall in group II soils ($679 \times 10^3$ CFU/100 ml) and lowest in group IV soils ($330 \times 10^3$ CFU/100 ml), with an overall mean of $520 \times 10^3$ CFU/100 ml among all soil groups. This value is at least 10 times greater than normal FC loads observed in septic systems of 4-person households in Kentucky, suggesting significant overloading of the system studied. Group I and group III soils showed intermediate average concentrations ($628 \times 10^3$ CFU/100 ml and $406 \times 10^3$ CFU/100 ml, respectively), but somewhat greater temporal variability between samplings (Tables 2–5).

Average effluent concentrations were also variable between and within soil groups and soil depth treatments ranging from 5.0 CFU/100 ml in the 60-cm monolith of the Yeager soil (group I) to $311.6 \times 10^3$ CFU/100 ml in the

**Table 2** | Mean values +1 S.D. for the influent and effluent composition of the wastewater applied to the soil monoliths of Group I, percent removal efficiencies for each soil and depth, and percent daily compliance with EPA maximum discharge limit (MDL) recommended criteria†

| | | Influent (CFU x $10^3$ / 100 ml) | | Effluent (CFU x $10^3$ / 100 ml) | | Removal efficiency (%) | | Daily compliance (%) | |
|---|---|---|---|---|---|---|---|---|---|
| Soil | Depth (cm) | FC | FS | FC | FS | FC | FS | FC | FS |
| Yeager 1 | 30 | 940 ± 485 | 361 ± 254 | 20.4 ± 31.7 | 4.6 ± 6.5 | 98.1 ± 2.3 | 97.6 ± 4.6 | 36 | 50 |
| | 45 | 940 ± 485 | 361 ± 254 | 1.1 ± 1.7 | 0.4 ± 0.6 | 99.9 ± 0.2 | 99.7 ± 0.4 | 64 | 79 |
| | 60 | 940 ± 485 | 361 ± 254 | 0.1 ± 0.1 | 0.1 ± 0.1 | 100.0 ± 0.0 | 100.0 ± 0.0 | 100 | 100 |
| Yeager 2 | 30 | 330 ± 182 | 76.1 ± 54.4 | 32.2 ± 43.8 | 7.8 ± 9.0 | 85.5 ± 19.3 | 84.7 ± 26.1 | 21 | 43 |
| | 45 | 330 ± 182 | 76.1 ± 54.4 | 20.2 ± 30.3 | 5.3 ± 5.3 | 93.7 ± 9.8 | 82.1 ± 27.2 | 14 | 29 |
| | 60 | 330 ± 182 | 76.1 ± 54.4 | 72.8 ± 59.0 | 16.3 ± 13.7 | 73.3 ± 22.3 | 67.3 ± 27.1 | 7 | 0 |
| Mean | 30 | 613 ± 466 | 204 ± 217 | 26.3 ± 38.0 | 6.2 ± 7.9 | 91.8 ± 15.0 | 91.1 ± 19.5 | 29 | 47 |
| | 45 | 613 ± 466 | 204 ± 217 | 10.7 ± 23.2 | 2.9 ± 4.5 | 96.8 ± 7.5 | 90.9 ± 20.9 | 39 | 54 |
| | 60 | 613 ± 466 | 204 ± 217 | 36.4 ± 55.3 | 8.1 ± 12.6 | 86.6 ± 20.6 | 83.6 ± 25.1 | 54 | 50 |
| Overall mean | – | 628 ± 305 | 214 ± 143 | 24.5 ± 41.8 | 5.6 ± 9.1 | 91.8 ± 15.7 | 88.6 ± 22.0 | 40 | 50 |

†MDL for FC and FS = $1 \times 10^3$ CFU / 100 ml.

60-cm monolith of the Shelocta soil (group III). Overall mean effluent concentrations of FC were highest in group III soils, ($63.9 \times 10^3$ CFU/100 ml), particularly in the Shelocta soil, and lowest in group IV soils ($6.5 \times 10^3$ CFU/100 ml). These levels are between 6 and 60 times higher than the EPA recommended levels of $1 \times 10^3$ CFU/100 ml. Only six of the 30 soil monoliths used in the study had average FC effluent concentrations in compliance with the EPA criteria, including Yeager 1 (60-cm), Lily (60-cm), Nolin (all depths), and Lowell (30-cm) (Tables 2–5). In contrast, effluents from Yeager 2 (60-cm), Pope (45- cm), and Shelocta (45- and 60-cm) monoliths were from 73 to 311 times higher than the required levels. Daily monitoring compliance averaged 40% in group I soil monoliths, 55% in group II soil monoliths, 53% in group III soil monoliths, and 56% in group IV soil monoliths, suggesting a somewhat improved treatment by II, III, and IV group soils (Tables 2–5). Daily monitoring compliance improved with increasing soil depth from 42% in the 30-cm soil monoliths, to 47% in the 45-cm soil monoliths, to 64% in the 60-cm soil monoliths, indicating the advantage of the 60-cm soil thickness threshold for improving FC treatment (Tables 2–5).

Comparing FC effluent concentrations between soil groups without regard to soil depth treatments (Tables 2–5), soil groups I, II, and IV appeared to provide statistically superior treatment ($P < 0.05$) than soil group III, mainly due to poor performance by the Shelocta soil (Table 4). Considering soil depth treatments, group IV soils provided the best and most consistent overall treatment in all soil depths, although the differences with groups I and II at 30-cm soil depths were not statistically significant. There was significant variability in FC treatment even within soil groups. While Yeager 1 (group I), Lily and Pope (group II), Ashton (group III), and Maury (group IV) soils showed an improved treatment trend with increasing soil depth, especially at the 60-cm threshold, the remaining soils showed indifference or inconsistent response to soil thickness changes (Tables 2–5).

**Table 3** | Mean values +1 S.D. for the influent and effluent composition of the wastewater applied to the soil monoliths of Group II, percent removal efficiencies for each soil and depth, and percent daily compliance with EPA maximum discharge limit (MDL) recommended criteria†

| | | Influent (CFU x $10^3$ / 100 ml) | | Effluent (CFU x $10^3$ / 100 ml) | | Removal efficiency (%) | | Daily compliance (%) | |
|---|---|---|---|---|---|---|---|---|---|
| Soil | Depth (cm) | FC | FS | FC | FS | FC | FS | FC | FS |
| Bruno | 30 | 647 ± 606 | 217 ± 195 | 1.4 ± 1.6 | 1.1 ± 3.1 | 99.5 ± 1.0 | 99.8 ± 0.3 | 57 | 86 |
| | 45 | 647 ± 606 | 217 ± 195 | 6.9 ± 15.1 | 3.8 ± 7.5 | 99.0 ± 2.2 | 99.1 ± 1.7 | 79 | 71 |
| | 60 | 647 ± 606 | 217 ± 195 | 2.3 ± 5.5 | 0.1 ± 0.2 | 99.6 ± 0.9 | 99.9 ± 0.4 | 79 | 100 |
| Lily | 30 | 633 ± 629 | 198 ± 156 | 4.7 ± 5.6 | 1.9 ± 3.7 | 98.8 ± 1.5 | 99.2 ± 0.8 | 20 | 67 |
| | 45 | 633 ± 629 | 198 ± 156 | 3.9 ± 11.8 | 0.5 ± 1.3 | 99.4 ± 2.0 | 99.8 ± 0.4 | 73 | 93 |
| | 60 | 633 ± 629 | 198 ± 156 | 0.6 ± 1.9 | 0.1 ± 0.3 | 99.8 ± 0.5 | 99.8 ± 0.5 | 93 | 93 |
| Pope | 30 | 758 ± 321 | 42 ± 30 | 33.6 ± 53.1 | 2.3 ± 2.3 | 95.2 ± 6.1 | 94.1 ± 6.7 | 21 | 36 |
| | 45 | 758 ± 321 | 42 ± 30 | 201.8 ± 166.8 | 11.7 ± 9.1 | 70.8 ± 21.6 | 72.5 ± 14.4 | 0 | 7 |
| | 60 | 758 ± 321 | 42 ± 30 | 9.1 ± 18.4 | 1.0 ± 1.8 | 98.2 ± 4.3 | 97.7 ± 4.8 | 71 | 71 |
| Mean | 30 | 671 ± 524 | 181 ± 213 | 13.2 ± 33.5 | 1.8 ± 3.0 | 97.8 ± 4.0 | 97.8 ± 4.6 | 33 | 63 |
| | 45 | 671 ± 524 | 181 ± 213 | 70.9 ± 133.1 | 5.3 ± 8.2 | 89.7 ± 18.3 | 99.5 ± 15.2 | 51 | 57 |
| | 60 | 671 ± 524 | 181 ± 213 | 3.9 ± 11.2 | 0.4 ± 1.1 | 99.2 ± 2.5 | 99.1 ± 2.9 | 81 | 88 |
| Overall mean | – | 679 ± 68 | 152 ± 96 | 29.5 ± 84.6 | 2.5 ± 5.5 | 95.6 ± 11.7 | 95.8 ± 10.0 | 55 | 69 |

†MDL for FC and FS = $1 \times 10^3$ CFU / 100 ml.

In spite of the substantial variability in influent and effluent FC concentrations between soil groups and soil depth treatments, percent removal efficiencies did not show drastic fluctuations, ranging from 63.7% in the Shelocta soil (60-cm) to 100.0% in Yeager 1 (30-cm) soil (Tables 2–5). Soil group mean percent removal efficiencies were much more similar, ranging from 90.5% in group III to 95.6% in group II soils. Over all soil depths, there were no statistical differences among soil groups, except between group II and III soils, but groups II and IV out-performed statistically ($P < 0.05$) groups I and III at the 60-cm soil depth (Tables 2–5).

The above data indicate the magnitude of the variability in influent and effluent FC concentrations that could be observed in on-site septic systems, even under the recommended constant nominal hydraulic load. Even though group IV soils appeared to have a statistically significant slight edge over other soil groups in FC removal, the effect of increasing soil depth on treatment performance was not clear. However, in terms of daily monitoring compliance for FC, there was a clear advantage in using the 60-cm depth in all soil groups over the 30- or 45-cm soil thickness. The data also document how misleading may be the use of % removal efficiency as a criterion for assessing treatment differences between soil groups. Even though the mean % removal efficiencies for FC for all soil groups were >90.5%, only 20% of the soil monoliths were in compliance with EPA criteria. This trend contradicts data reported by Anderson *et al.* (1994), and Ayres Associates (1993) indicating retention of most fecal bacteria within 60 to

**Table 4** | Mean values +1 S.D. for the influent and effluent composition of the wastewater applied to the soil monoliths of Group III, percent removal efficiencies for each soil and depth, and percent daily compliance with EPA maximum discharge limit (MDL) recommended criteria†

| | | Influent (CFU x $10^3$ / 100 ml) | | Effluent (CFU x $10^3$ / 100 ml) | | Removal efficiency (%) | | Daily compliance (%) | |
|---|---|---|---|---|---|---|---|---|---|
| **Soil** | **Depth (cm)** | **FC** | **FS** | **FC** | **FS** | **FC** | **FS** | **FC** | **FS** |
| Ashton | 30 | 235 ± 138 | 140 ± 134 | 33.8 ± 35.0 | 20.9 ± 26.3 | 83.9 ± 21.1 | 86.8 ± 16.7 | 14 | 14 |
| | 45 | 235 ± 138 | 140 ± 134 | 10.7 ± 13.5 | 12.8 ± 19.0 | 94.4 ± 10.0 | 88.6 ± 22.5 | 29 | 36 |
| | 60 | 235 ± 138 | 140 ± 134 | 2.9 ± 5.2 | 1.6 ± 4.0 | 98.9 ± 1.5 | 97.7 ± 5.3 | 64 | 86 |
| Nolin | 30 | 98 ± 93 | 126 ± 151 | 0.1 ± 0.2 | 0.1 ± 0.1 | 99.9 ± 0.1 | 100.0 ± 0.0 | 100 | 100 |
| | 45 | 98 ± 93 | 126 ± 151 | 0.1 ± 0.2 | 0 ± 0 | 99.9 ± 0.1 | 100.0 ± 0.0 | 100 | 100 |
| | 60 | 98 ± 93 | 126 ± 151 | 0.1 ± 0.2 | 0.1 ± 0.1 | 99.9 ± 0.1 | 100.0 ± 0.0 | 100 | 100 |
| Shelocta | 30 | 886 ± 1026 | 26 ± 37 | 46.4 ± 58.3 | 0.3 ± 0.5 | 90.9 ± 10.5 | 95.7 ± 6.1 | 29 | 93 |
| | 45 | 886 ± 1026 | 26 ± 37 | 142.4 ± 240.0 | 0.3 ± 0.4 | 87.4 ± 17.8 | 95.2 ± 8.2 | 43 | 86 |
| | 60 | 886 ± 1026 | 26 ± 37 | 311.6 ± 373.0 | 4.5 ± 6.4 | 63.7 ± 25.2 | 70.8 ± 36.1 | 0 | 43 |
| Mean | 30 | 427 ± 702 | 95 ± 126 | 28.1 ± 43.7 | 7.1 ± 17.8 | 91.3 ± 14.9 | 94.3 ± 10.9 | 48 | 69 |
| | 45 | 427 ± 702 | 95 ± 126 | 53.6 ± 153.7 | 4.2 ± 12.0 | 93.6 ± 12.9 | 94.9 ± 13.7 | 57 | 74 |
| | 60 | 427 ± 702 | 95 ± 126 | 110.1 ± 262.3 | 2.1 ± 4.7 | 86.6 ± 22.8 | 88.6 ± 25.6 | 55 | 76 |
| Overall mean | – | 406 ± 421 | 97 ± 62 | 63.9 ± 179.2 | 4.5 ± 12.9 | 90.5 ± 17.5 | 92.7 ± 17.8 | 53 | 73 |

†MDL for FC and FS = $1 \times 10^3$ CFU / 100 ml.

90 cm of the infiltrative surface. Although compliance level is expected to improve over time in soil leach-fields due to biomat development (University of Wisconsin 1978), the extremely high FC levels in many effluents reveal the risks of employing % removal efficiencies as a basis for performance comparisons. Furthermore, the data demonstrate that soil texture alone may not explain the efficiency of various soils to remove FC. Filtration is considered to be the dominant mechanism for FC removal by soils. The filtration efficiency is enhanced by the slow hydraulic conductivity of fine-textured soils assuming a uniform soil matrix (Brown *et al.* 1977; Canter & Knox 1985). However, the matrix of most soils is anything but uniform, considering spaces occupied by roots, macropores, and rock fragments. In many cases finer-textured soils have more extensive macroporosity, and therefore less soil matrix uniformity than coarse-textured soils. Since FC are mainly colloid size bacteria they can migrate easily through soil macropores without being attenuated by the soil matrix (Hagedorn 1982; Tchobanoglous & Burton 1991; Coyne *et al.* 1997). Therefore, in soils with extensive macroporosity FC removal efficiency may be more controlled by the total volume and size of pore space available for transport rather than the amount of clay or the texture of the soil matrix.

## Fecal streptococci

Influent fecal streptococci (FS) concentrations varied considerably between soil groups and sampling periods, ranging from as low as 500 CFU/100 ml in group III soils to

**Table 5** | Mean values +1 S.D. for the influent and effluent composition of the wastewater applied to the soil monoliths of Group IV, percent removal efficiencies for each soil and depth, and percent daily compliance with EPA maximum discharge limit (MDL) recommended criteria†

| | | Influent (CFU x $10^3$ / 100 ml) | | Effluent (CFU x $10^3$ / 100 ml) | | Removal efficiency (%) | | Daily compliance (%) | |
|---|---|---|---|---|---|---|---|---|---|
| **Soil** | **Depth (cm)** | **FC** | **FS** | **FC** | **FS** | **FC** | **FS** | **FC** | **FS** |
| Lowell | 30 | 201 ± 169 | 84 ± 48 | 0.1 ± 0.1 | 0.1 ± 0.1 | 99.9 ± 0.1 | 99.9 ± 0.1 | 100 | 100 |
| | 45 | 201 ± 169 | 84 ± 48 | 8.9 ± 17.1 | 2.7 ± 5.2 | 96.8 ± 5.4 | 96.1 ± 7.8 | 71 | 71 |
| | 60 | 201 ± 169 | 84 ± 48 | 3.8 ± 6.7 | 1.2 ± 1.9 | 98.6 ± 2.2 | 98.6 ± 2.3 | 57 | 71 |
| Maury | 30 | 456 ± 434 | 649 ± 426 | 12.7 ± 10.8 | 4.6 ± 3.3 | 90.7 ± 10.2 | 98.2 ± 2.5 | 20 | 33 |
| | 45 | 456 ± 434 | 649 ± 426 | 10.8 ± 9.3 | 2.6 ± 2.7 | 82.1 ± 34.5 | 98.9 ± 2.1 | 13 | 40 |
| | 60 | 456 ± 434 | 649 ± 426 | 2.4 ± 5.7 | 0.1 ± 0.2 | 99.4 ± 1.6 | 100.0 ± 0.1 | 73 | 93 |
| Mean | 30 | 333 ± 381 | 368 ± 415 | 6.4 ± 9.9 | 2.2 ± 3.2 | 95.3 ± 8.5 | 99.1 ± 1.9 | 60 | 67 |
| | 45 | 333 ± 381 | 368 ± 415 | 9.9 ± 13.6 | 2.6 ± 4.0 | 89.5 ± 25.3 | 97.5 ± 5.7 | 42 | 56 |
| | 60 | 333 ± 381 | 368 ± 415 | 3.1 ± 6.1 | 0.7 ± 1.4 | 99.0 ± 1.9 | 99.3 ± 1.8 | 65 | 82 |
| Overall mean | – | 330 ± 128 | 367 ± 283 | 6.5 ± 10.6 | 1.8 ± 3.2 | 94.6 ± 15.8 | 98.6 ± 3.7 | 56 | 68 |

†MDL for FC and FS = 1x$10^3$ CFU / 100 ml.

as high as 1,425 × $10^3$ CFU/100 ml in group IV soils. Total average concentrations were highest overall in group IV soils (367 × $10^3$ CFU/100 ml) and lowest in group III soils (97 × $10^3$ CFU/ml), with an overall mean of 198.4 × $10^3$ CFU/100 ml among all soil groups. Soil groups I and II showed intermediate average concentrations (214 × $10^3$ and 152 × $10^3$ CFU/100 ml, respectively) and moderate temporal variability between samplings (Tables 2–5).

Average effluent FS concentrations were also variable between and within soil depth treatments, with the lowest (0) and the highest (20.9 × $10^3$ CFU/100 ml) values being observed within the same soil group (45-cm monoliths of the Nolin soil, and 30-cm monoliths of the Ashton soil, respectively) (Table 4). Overall, mean effluent concentrations of FS were highest in group I soils (5.6 x $10^3$ CFU/100 ml) and lowest in group IV soils (1.8 x $10^3$ CFU/100 ml), with the Ashton (group III) and Yeager 2 (group I) soils showing the worst attenuation efficiency. Only 13 of the 30 soil monoliths used in the study had average effluent FS levels in compliance with the EPA criteria of 1000 CFU/100 ml, including two monoliths from soil group I, four monoliths from soil group II, five monoliths from soil group III, and 2 monoliths from soil group IV (Tables 2–5). Of the monoliths complying with the EPA criteria, 6 represented the 60- cm soil depth treatment, 4 the 45-cm soil depth treatment and 3 the 30-cm soil depth treatment. However, daily monitoring compliance was higher than that observed for FC, averaging 50% in group I soil monoliths, 69% in group II soil monoliths, 73% in group III soil monoliths, and 69% in group IV soil monoliths (Tables 2–5). Daily monitoring compliance regardless of soil group increased from 60% in the 30- and 45-cm soil monoliths to 75% in the 60- cm soil monoliths, suggesting a consistent treatment improvement with increasing soil depth (Tables 2–5).

Comparing FS effluent concentrations between soil groups without regard to soil depth treatments soil group IV appeared to provide statistically superior treatment ($P < 0.05$) than soil group I, with soil groups II and III providing intermediate treatment (Tables 2–5). Considering soil depth treatments for the removal of FS, there were no statistical differences between groups for the 30- and 45-cm soil depths, but the 60- cm soil depth of soil groups II, III, and IV clearly outperformed ($P < 0.05$) soil group I (Tables 2–5). Significant variability in FS effluents was also evident within soil groups, with Yeager 1 (group I), Lily (group II), Ashton (group III), and Maury (group IV) showing an improved treatment trend with increasing soil depth, while the behavior of the remaining soils was inconsistent, as was the case with FC (Tables 2–5).

Percent removal efficiencies for FS ranged from as low as 67.3% in the 60-cm soil monolith of the Yeager 2 soil (group I) to as high as 100% in the 60-cm soil monoliths of the Yeager 1 soil (group I), the three monoliths of the Nolin soil (group III), and the 60-cm monolith of the Maury soil (group IV) (Tables 2–5). In spite of the narrow mean percent removal efficiency range between soil groups (88.6% to 98.6%), soil group IV provided statistically superior treatment ($P < 0.05$) to soil groups I and III, while group II provided intermediate treatment. Although there were no clear- cut percent removal efficiency differences between soil groups at the 30- and 45-cm soil depths, soil groups II and IV appeared to provide statistically superior treatment ($P < 0.05$) to soil groups I and III at the 60-cm soil depth (Tables 2–5). This trend is consistent with data reported by Van Cnyk et al. (2001) indicating that near complete removal of fecal bacteria may require 60-90 cm vertical distance separation in sandy soils.

In spite of the substantial variability in influent and effluent FS concentrations the results of the study indicated a slight but statistically significant ($P < 0.05$) advantage in the treatment of FS by group IV over group I soils, with the evidence becoming stronger at the 60-cm soil depth. When we consider all soil groups, >45% of the 60-cm soil monoliths met MDL criteria compared to <30% only for the 30- and 45-cm soil monoliths, while showing consistent improvement in daily monitoring compliance. Even though the advantage of finer textured soils and greater soil thickness for FS removal is much more evident than that of FC removal, temporal waste loading fluctuations and soil macroporosity may considerably skew treatment efficiency beyond the anticipated effects of soil texture alone. This is particularly relevant to FS removal because the main treatment mechanism involved is very similar to that of FC attenuation (filtration).

## SUMMARY AND CONCLUSIONS

Fecal coliform removal and daily compliance was poor in all soil groups due to much higher than anticipated influent levels. Even though there were no statistical differences ($P < 0.05$) in treatment efficiency between soil groups and soil depths, soil group IV showed the lowest overall effluent FC concentrations and the 60- cm soil depth with all soil groups combined the highest percent daily compliance with EPA criteria. Treatment efficiency for FS was somewhat better than FC, but daily compliance was still generally low. In spite of significant variability within soil groups, effluent FS concentrations from fine-textured soil monoliths were substantially lower than those of coarse-textured soils, particularly at the 60-cm soil depth, which also showed considerably higher percent daily compliance (1000 CFU/100 ml) than any other soil depth.

Generally, despite the slight improvement in fecal bacteria treatment efficiency and daily compliance with increasing soil clay content and soil depth, none of the soil groups provided adequate treatment. Biomat development is expected to improve treatment, but the high influent levels of fecal bacteria pose great concerns for surface and groundwater contamination. It is clear from the findings of this study that a minimum vertical separation distance of 30-cm between the bottom of the leach-field trench and a limiting interface may not be sufficient in providing adequate treatment for fecal bacteria removal, particularly in coarse-textured soils. The results 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). 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 documentation 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, re-circulating sand-filters, peat or drip-irrigation systems are among a few complementary or alternative technologies which have been used successfully in other States as substitutes for the lack of sufficient suitable soil depth.

## ACKNOWLEDGEMENTS

Funding for this project was provided in part by a grant from the U.S. Environmental Protection Agency (USEPA) through the Kentucky Division of Water, Nonpoint Source Section as authorized by the Clean Water Act Amendments of 1987, §319(h). The authors would like to thank the Kentucky Department of Health and USDA-NRCS personnel for their assistance and cooperation in site identification.

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Available online April 2006