Effects of Swine Manure Application on Bacterial Quality of Leachate from Intact Soil Columns

E. A. Warnemuende, R. S. Kanwar

Abstract. *Excessive application of swine manure on agricultural lands is likely to increase water pollution. Potential impacts of swine manure management on bacterial contamination in subsurface drainage are often difficult to assess in the field. In this study, leachate from intact 20–cm (8–in.) diameter, 30–cm (12–in.) long soil columns receiving simulated fall and spring manure applications at 168 kg N/ha (150 lb N/ac) and 336 kg N/ha (300 lb N/ac) was analyzed for bacterial densities. The fall soil columns were frozen for 7 weeks between manure application and irrigation. Soil columns were collected in sterile galvanized tubing using a Giddings probe and 20–cm bit adapter. Fecal coliform,* E. coli*, and enterococci densities in leachate from the columns were determined for four weekly irrigation events following manure application. While a positive trend between the manure application rate and bacterial densities in the leachate water was observed, this effect was not generally statistically significant at the 10% level. However, an interaction between the application rate and timing was observed, suggesting that an increase in application rate is more likely to cause greater bacterial contamination in subsurface drainage for spring application than for fall application. Bacterial densities in leachate were most often significantly higher where manure had been applied in the spring at 336 kg N/ha, versus the other manure treatments. Additionally, less bacterial leaching was observed in fall manure–applied columns as compared to the spring manure–applied columns. Bacterial densities in leachate from fall manure–applied soil columns were significantly lower in comparison with bacterial densities in leachate from the spring manure–applied soil columns at the 10% level during the second, third, and fourth irrigation events.*

Keywords. *Land application, Swine manure, Bacterial leaching, Soil column, Fecal contamination,* E. coli*, Fecal coliform, Enterococci.*

Where livestock manure is land applied, the potential for fecal contamination of receiving waters exists. Several pathogens that pose a health risk to humans are associated with fecal material. Fecal pathogens that may become waterborne include: *Escherichia coli* (*E. coli*), *Salmonella sp.*, *Campylobacter sp.*, *Shigella sp.*, *Giardia*, and *Cryptosporidium* (Mawdsley et al., 1995). Because it is often difficult and expensive to detect these pathogenic organisms within desired detection limits, indicator organisms are used to detect fecal contamination and predict the likelihood of the presence of pathogenic organisms. Microbial water quality is usually described in terms of common indicator bacteria, such as fecal coliform, *E. coli* (a subpopulation of fecal coliform), fecal streptococci, and enterococci. Microbial water quality determines the suitability of a water body for both drinking and recreational uses. Drinking water must have less than one CFU/100 mL total coliforms (zero colony forming units in a sample volume of 100 mL), and the maximum allowable limit for fecal coliform in recreational waters (limited contact) is 200 CFU/100 mL. Current manure application guidelines do not explicitly prevent the introduction of pathogenic microorganisms to surface water and groundwater. Therefore, it is important to identify optimum manure application procedures, which can minimize bacterial pollution from land application while maintaining crop yield. Specific manure application parameters include application method, timing, and rate. It is necessary to optimize these application parameters to maximize manure benefit, while minimizing the pollution potential from the use of manure.

The objective of this study was to identify swine manure application timing and rate effects on bacterial water quality as an aid in manure application decision making. Specifically, the impacts of different manure management regimes on fecal coliform, *E. coli*, and enterococci populations in leachate from intact soil columns were examined. Several previous studies have investigated bacterial transport in the field setting (Culley and Phillips, 1982; Joy et al., 1998; Warnemuende, 2000). This study supplements existing research by comparing manure application timing and rate effects in a controlled laboratory setting, where the impacts of field variability and background biological activity are minimized.

Article was submitted for review in February 2002; approved for publication by the Soil & Water Division of ASAE in August 2002.

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  ISSN 0001–2351

Bacterial Transport to Subsurface Drain Water

Bacterial movement to subsurface drainage water may contribute to surface water contamination via base flow and/or artificial tile drainage, or groundwater contamination via bacterial leaching. When bacteria are introduced to the soil through land application of manure, the rate at which they reach the depth of drain tile or aquifer is of great interest. The leaching of viable bacteria in the subsurface, which is a function of both bacterial movement and survival, is site and organism specific, and varies with atmospheric conditions and water and manure characteristics. This section addresses the factors that govern the transport of bacteria in the subsurface.

Soil Characteristics

Texture and particle size distribution affect straining processes. A study by Jang et al. (1983) showed straining to contribute significantly to the removal of bacteria from leachate where the average bacteria cell size was greater than the size of at least 5% of particles. Pore size may contribute to filtration removal, sedimentation of bacteria in pores, and consequent reduction of permeability of the soil (Peterson and Ward, 1989). Studies by Abu–Ashour et al. (1998) and Smith et al. (1985) found macropore flow to constitute a major pathway for bacterial contamination of effluent discharged from columns. In a 1998 field study, Scott et al. found that preferential flow accounted for rapid transport of fecal coliform to tile lines at the 90 cm depth on fields where dairy manure had been applied. Because of the major role of preferential flow in bacterial transport in the field and in intact soil columns, bacterial trends in leachate from intact soil columns better represent bacterial movement in the field setting versus their repacked counterparts, and they are useful in predicting bacterial trends in tile water from a similar soil.

Several soil characteristics influence bacterial sorption, and thus bacterial transport. Because bacteria sorb more readily to positively charged mineral surfaces than to negatively charged mineral surfaces (Scholl et al., 1990), mineral makeup of the soil impacts bacterial sorption. Organic matter can affect the surface charge and hydrophobicity characteristics of the base mineral (Harvey, 1991) and increase surface area and sorption sites. Properties of organic matter and clay particles present in soil are believed to dominate the processes governing microbial adsorption. Soil pH influences the pH of infiltrating water. While the pH effects on bacterial sorption are dependent on soil and organism characteristics, bacterial retention is generally higher in neutral to acidic conditions than in alkaline conditions (Goldschmidt et al., 1973).

Moisture Properties

Physical and moisture conditions such as soil water content, temperature, and flux, impact bacterial transport (Hagedorn and McCoy, 1979; Yates and Yates, 1988). These factors influence the processes of advection and dispersion, as well as bacterial adsorption. High moisture content and flow rate contribute to bacterial leaching. Hagedorn and McCoy (1979) found that bacteria generally move less than 1 m under unsaturated conditions, but can move 30 to 60 m under saturated conditions. The pH and ionic strength of infiltrating water impact bacterial transport by the same mechanisms as the pH and ionic strength of the soil.

Bacterial Characteristics

The density and dimensions of the microorganism affect the processes of straining and gravitational leaching. In saturated conditions, bacteria may become mobile by means of their own locomotion. This mobility depends on the type of microorganism, but has been shown to be a significant means of transport for motile strains of *E. coli* (Reynolds et al., 1989). A study by Huysman and Verstraete (1993) showed that cell surface hydrophobicity impacts bacterial transport. In this study, hydrophobic bacteria adhered to the soil more readily than hydrophillic bacteria. Cell surface charge may also play a role in bacterial transport (Sharma et al., 1985).

Bacterial Survival in the Subsurface

The survival rate of microorganisms introduced to soil is a function of many factors. The relative influence of each factor depends on whether it is a limiting or excessive variable to bacterial survival in the soil microenvironment. The dominating factors tend to change throughout the year, as seasonal variations in factors such as light (Bell, 1976; Kovacs and Tamasi, 1979), temperature, and moisture conditions take place. Because of this, timing of manure application may be critical to bacterial persistence in the soil. The major controlling factors are believed to be pH, moisture, temperature, and nutrient supply.

Soil and Environmental Factors

Extreme pH values, both high and low, decrease bacterial survival. This effect has also been observed in pathogens in manure slurry (Williams, 1979) and in viruses in the soil (Hurst et al., 1980). A study by McFeters and Stuart (1972) found that bacterial die–off was minimized at a pH range from 6 to 7.

Above 4° C, lower temperatures are generally more favorable to bacterial survival than higher temperatures (Zibilske and Weaver, 1978). Between 5° C and 30° C, die–off rate of fecal bacteria generally doubles with each 10° C increase in temperature (McFeters and Stuart, 1972). Freeze–thaw cycles are detrimental to bacterial survival, although additional research is needed to clarify this effect.

Because bacterial populations are restricted to the aqueous phase and the solid–liquid interface, soil moisture content greatly impacts bacterial survival in the subsurface. Kibbey et al. (1978) found that survival rates of fecal bacteria increased with soil moisture content over a range of temperatures. In this study, the survival rate of fecal streptococci was found to be maximum where the soil was saturated.

The availability of nutrients in the soil and water is required for bacterial survival. Bacteria present in manure generally have access to a high nutrient supply prior to application. Enteric organisms do not readily adapt to the lower nutrient availability in the soil environment post–application (Klein and Casida, 1967) and therefore experience die–off relative to the soil nutrient supply. Where organism density in manure is high, competition for nutrients lowers nutrient availability and bacterial survivability. Klein and Casida (1967) observed an increase in initial bacterial die–off where inoculum size was increased by several orders of magnitude.

In some soil environments, predatory action by indigenous soil microfauna inhibits the survival of fecal bacterial populations in the subsurface. Additionally, competition from indigenous populations may hinder bacterial survival. Some organisms, which may be native to application–site soils, produce antibiotics or toxic substances that can increase bacterial die–off.

Manure Application Parameters

The method of manure application has been found to influence bacterial survival. Giddens et al. (1973) found that die–off rate of fecal coliform from poultry waste was lowered by 50% where manure was applied to the surface, rather than incorporated. In a study by Gagliardi and Karns (2000), manure application was found to contribute to *E. coli* O157:H7 reproduction in intact soil cores that simulated no–till soil, but was found to hinder reproduction in disturbed cores that simulated tilled soil. However, there was no significant difference in the level of *E. coli* O157:H7 in leachate from the till and no–till treatments at the 5% level. Results of a lysimeter study by Stoddard et al. (1998) showed that tillage did not significantly affect bacterial mortality rates or bacterial densities in leachate. The same study revealed generally greater bacterial leaching from spring manure application versus fall manure application, with fecal coliform mortality significantly delayed and higher fecal streptococci mortality resulting from spring applications. These timing effects were not statistically significant.

Methodology

Experimental Apparatus

In this study, 30–cm intact soil columns were used to make relative predictions regarding bacterial trends in tile water. Although tile drains typically exist at the 90 to 120 cm depth, 30–cm soil columns were selected for their stability and unit profile length. Several relationships between bacterial densities and depth from source have been developed (Corapcioglu and Haridas, 1984).

Experimental treatments varied by timing and rate of manure application. Spring and fall applications at the recommended rate for corn in corn/soybean annual rotation for the site (168 kg N/ha) and at double the recommended rate (336 kg N/ha) were examined. Soil column treatments are listed in table 1.

Eighteen soil columns were collected from the Iowa State University Agronomy and Agricultural Engineering Research center near Ames, Iowa, in order to accommodate three replications of the four manure treatments and two control treatments. The soil was a Clarion loam in annual corn and soybean rotation with the characteristics listed in table 2. Soil columns were extracted in late fall, after the 1999 soybean harvest, using a Giddings probe and a 20–cm bit adapter. The 30–cm long columns were extracted in 38–cm long sections of sterilized galvanized tubing that had been sharpened on the down–facing edge. In order to detect compaction, the vertical distance between the top edge of the column and the inside soil surface was measured and compared to the vertical distance between the top edge of the column and the outside soil surface, prior to extraction of each soil column. No compaction was detected.

Table 1. Experimental treatments.

Treatment	Description
Spring control	Not amended
Spring manure 1×	Manure application, 168 kg N/ha (150 lb N/ac)
Spring manure 2×	Manure application, 336 kg N/ha (300 lb N/ac)
Fall control	Not amended
Fall manure 1×	Manure application, 168 kg N/ha (150 lb N/ac)
Fall manure 2×	Manure application, 336 kg N/ha (300 lb N/ac)

Table 2. Soil characteristics.

Depth (cm)	N (ppm)	P (ppm)	K (ppm)	pH	OM (%)	Bulk Density (g/cm^3)	Moisture (% vol.)
0 to 15	1.5	18.9	96.1	6.8	2.9	1.4	19.2
15 to 30	1.4	9.3	85.4	6.1	2.5	1.5	19.2

The soil columns were placed in a growth chamber for environmental simulation. Autoclaved screen was installed on the bottom of each column in order to prevent soil loss. The columns were then arranged in a random block design in a leachate collection apparatus consisting of 25–cm autoclaved funnels and a guide table that prevented the columns from deviating from the vertical position (fig. 1). They were saturated with 5000 mL of tap water and allowed to drain for 4 days.

Environmental Simulation

The initial growth chamber program simulated the soil temperature at the 10–cm depth during the typical periods of fall and spring manure application. The growth chamber temperature was set to reflect the average daily minimum and maximum soil temperature fluctuations at the 10–cm depth, using a ten–year average from data collected at the experimental site from which the columns were extracted. The average daily minimum soil temperature occurred during 12 hours of darkness and was followed by 12 hours of the average daily maximum soil temperature during 12 hours of light. Soil temperature was chosen over air temperature for the growth chamber program because of the semi–exposed condition of the soil columns, which is in contrast to the less exposed condition of a similar soil profile in situ. In this way, buffering of air temperature fluctuations, which significantly

Figure 1. Soil columns in the leachate collection apparatus.

Table 3. Manure characteristics.

Moisture (%)	91.60
Nitrogen (%)	0.50
Calcium (%)	0.25
Phosphorus (%)	0.18
P_2O_5 (%)	0.39
Potassium (%)	0.12
K_2O (%)	0.14
Magnesium (%)	0.09
Sulfur (%)	0.03
Sodium (%)	0.03
Zinc (ppm)	44.67
Manganese (ppm)	17.33
Copper (ppm)	5.00
Iron (ppm)	213.33
Cobalt (%)	>1
NH_3–N (ppm)	2234.00

affects soil temperature at depth, was built in to the growth chamber temperature program.

Following manure application, the program reflected typical continued May temperature and irrigation conditions for the spring columns. Six days after manure application, fall soil columns were sealed and subjected to seven weeks of freezing and darkness, to simulate over–winter conditions of below–freezing temperatures and snow cover, and to produce the cell changes associated with freezing and thawing. After this period, the fall columns were transported to a growth chamber simulating the same time period as the spring columns. According to field data (Warnemuende, 2000), this is the period during which bacterial leaching occurs on fall–manured plots as well as spring–manured plots. The temperature regime is illustrated in figure 2.

Irrigation and Leachate Monitoring

Six days after manure application, the first of four irrigation events took place on the spring columns. Tap water was irrigated to a ponding depth of 5.3 cm (volume = 1700 mL), which is a typical weekly rainfall amount for the first week in May. Weekly rainfall depths were based on weekly rainfall data and irrigated in a single event in order to produce the effects of macropore flow and yield enough leachate to perform bacterial analyses. The leachate was collected in sterile plastic sample bottles and analyzed for fecal coliform, *E. coli*, and enterococci using membrane filtration techniques (APHA, 1992). This process was repeated for the second, third, and fourth irrigation events. Ponding depth for these events was 3.7 cm (volume = 1200 mL), 3.4 cm (volume = 1100 mL), and 3.4 cm (volume = 1100 mL), respectively. Outflow was quantified in order to provide data necessary to complete water budgets on each column. Average outflows between treatments were similar.

Irrigation events on the fall soil columns began 2 days after return to May conditions. The depth and timing of fall soil column irrigation events were the same as the depth and timing of spring column irrigation events.

Moisture Content Monitoring

A mass evaluation was performed on three representative soil columns. Prior to each irrigation event, these columns were weighed. The mass of outflow was monitored using volumetric analysis of leachate samples. The mass data were used in conjunction with moisture analysis of the columns after the completion of the study in order to model the water budget for each column.

Results

The response of bacterial densities in leachate from manure–treated columns to successive irrigation events is illustrated in figures 3 through 5. Data for all treatments and controls are given in tables 4 through 7, where bacterial levels noted with the same lowercase letters are not significantly different.

While bacterial densities were higher in leachate from double–rate manure columns during event 1, no significant differences between manure treatments were detected during this event. However, with the exception of enterococci, bacteria were not detected in the control columns after the first irrigation event, and leachate bacterial densities from the control columns were always significantly less than those from manure–treated columns. Enterococci have a high degree of survivability in the soil. For this reason, contamination effects of wildlife activity or manure transportation on the soil column extraction site prior to soil column extraction would be most visible and most persistent in enterococci densities. Bacterial densities in leachate resulting from irrigation event 1 are illustrated in figure 6.

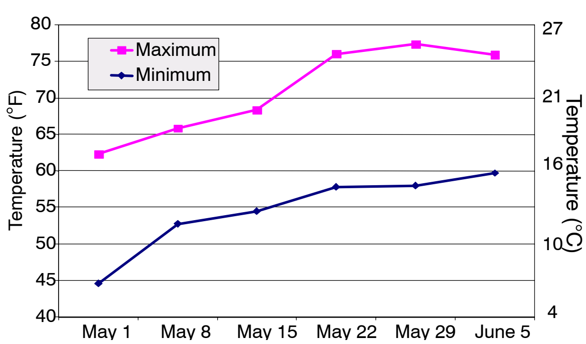

Figure 2. Average daily soil temperature at the 10 cm (4 in.) depth.

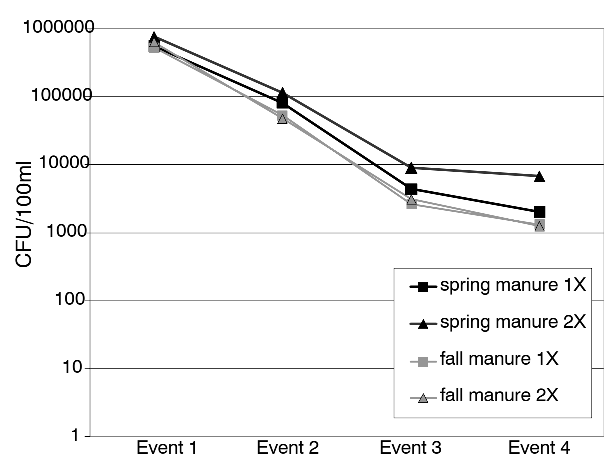

Figure 3. Fecal coliform density in soil column leachate from manure–treated columns.

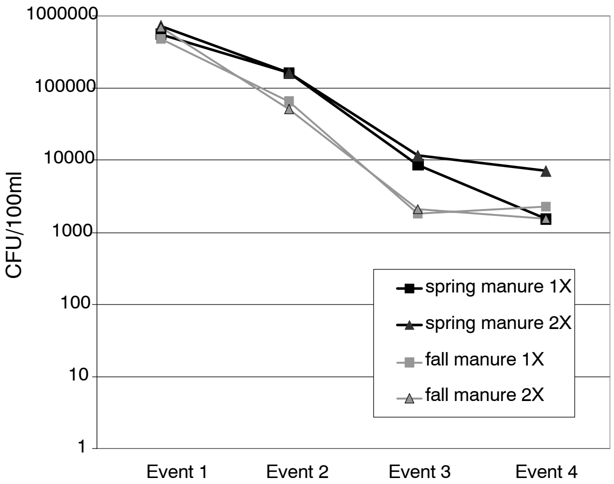

Figure 4. *E. coli* density in soil column leachate from manure–treated columns.

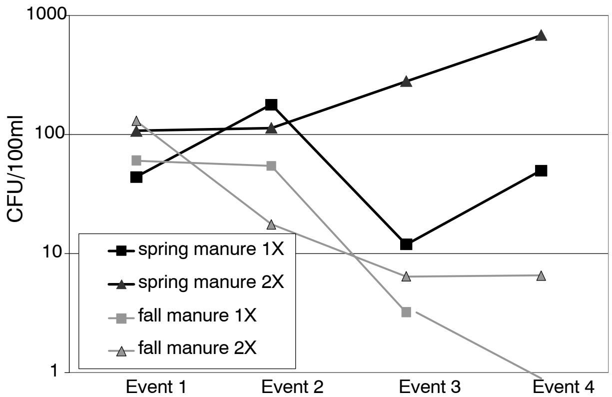

Figure 5. Enterococci density in soil column leachate from manure–treated columns.

Table 4. Bacterial densities in soil column leachate from event 1.

Treatment	Fecal Coliform (CFU/100 mL)		*E. coli* (CFU/100 mL)		Enterococci (CFU/100 mL)	
Spring control	1	b	3	b	6	a
Spring manure 1×	561892	a	560541	a	45	a
Spring manure 2×	762000	a	730000	a	108	a
Fall control	0	b	0	b	3	b
Fall manure 1×	528290	a	481974	a	61	a
Fall manure 2×	640201	a	700482	a	131	a

Table 5. Bacterial densities in soil column leachate from event 2.

Treatment	Fecal Coliform (CFU/100 mL)		*E. coli* (CFU/100 mL)		Enterococci (CFU/100 mL)	
Spring control	0	b	0	c	25	ab
Spring manure 1×	80310	a	161067	a	179	a
Spring manure 2×	114500	a	162272	a	114	a
Fall control	0	b	0	c	0	b
Fall manure 1×	52311	a	65333	ab	55	ab
Fall manure 2×	47250	a	50600	b	18	ab

Table 6. Bacterial densities in soil column leachate from event 3.

Treatment	Fecal Coliform (CFU/100 mL)		*E. coli* (CFU/100 mL)		Enterococci (CFU/100 mL)	
Spring control	0	b	0	d	0	b
Spring manure 1×	4353	a	8641	ab	12	ab
Spring manure 2×	9108	a	11536	a	283	a
Fall control	0	b	0	d	0	b
Fall manure 1×	2656	a	1832	c	3	ab
Fall manure 2×	3134	a	2113	bc	7	ab

Table 7. Bacterial densities in soil column leachate from event 4.

Treatment	Fecal Coliform (CFU/100 mL)		*E. coli* (CFU/100 mL)		Enterococci (CFU/100 mL)	
Spring control	0	c	0	c	1	a
Spring manure 1×	2054	b	1518	b	50	a
Spring manure 2×	6822	a	7059	a	682	a
Fall control	0	c	0	c	0	a
Fall manure 1×	1322	b	2268	b	0	a
Fall manure 2×	1243	b	1546	b	7	a

Event 2 resulted in higher bacterial densities in leachate from spring columns receiving double the manure application rate, and in lower bacterial densities in leachate from fall columns receiving double the manure application rate, although this difference was not significant (fig. 7). However, the effect of timing was significant during this event, with *E. coli* and enterococci densities significantly lower in fall column leachate than in spring column leachate. *E. coli* densities in leachate from spring columns were significantly higher than those in leachate from the fall double–rate columns.

As bacterial flushing and die–off progress, leachate bacterial levels generally continued to decline more rapidly during event 3. Bacterial quality of leachate resulting from event 3, shown in figure 8, was significantly influenced by both timing and rate, and was poorest among the spring double–rate columns. Spring double–rate columns resulted in significantly higher *E. coli* densities than fall single– and double–rate columns. Spring single–rate columns resulted in significantly higher *E. coli* densities in leachate than fall single–rate columns. Other differences between treatments were evident, although not statistically significant at the 10% level.

During event 4, spring double–rate columns continued to result in the poorest quality leachate (fig. 9). This treatment resulted in fecal coliform densities in leachate significantly higher than all other treatments, and *E. coli* densities higher than spring single–rate and fall double–rate treatments.

Discussion

Examining bacterial densities in leachate for successive irrigation events (figs. 3 through 5) reveals that fecal coliform densities followed a similar pattern to *E. coli* densities. This was expected since *E. coli*, as well as fecal coliform, belongs to the Enterobacteriaceae family and shares the common characteristics thereof. As previously discussed, cell wall and shape characteristics are major factors in microbial transport.

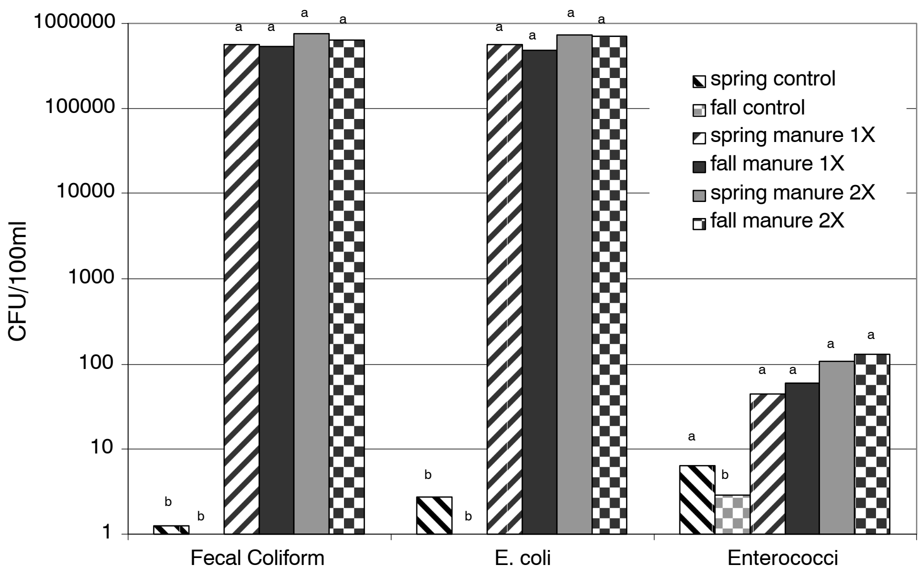

Figure 6. Bacterial densities in soil column leachate from event 1.

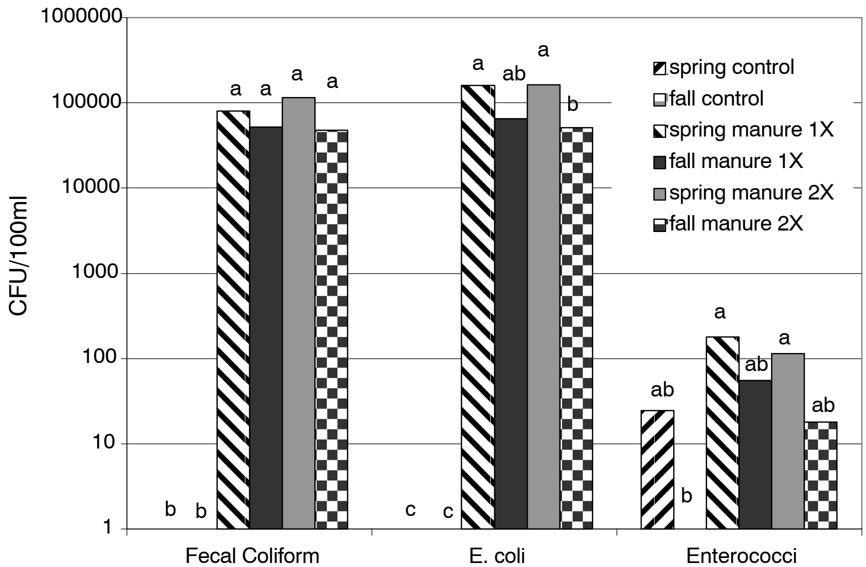

Figure 7. Bacterial densities in soil column leachate from event 2.

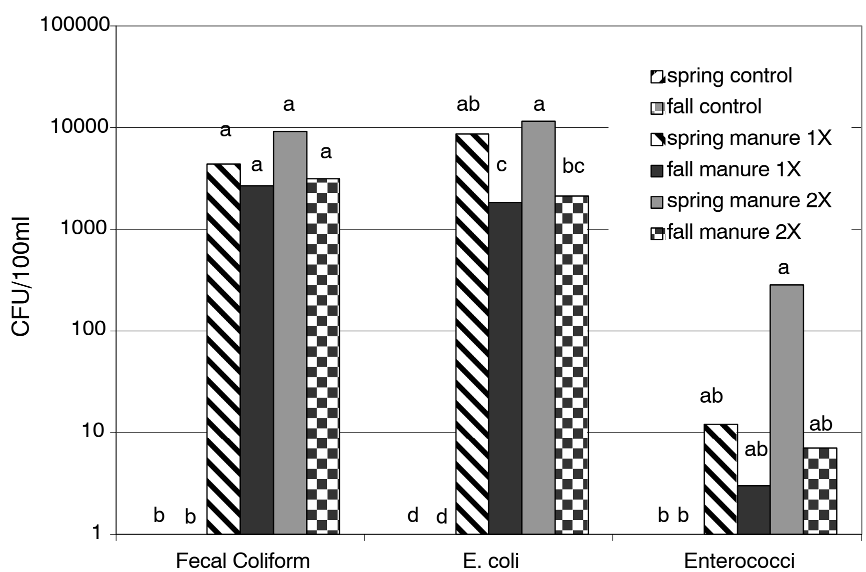

Figure 8. Bacterial densities in soil column leachate from event 3.

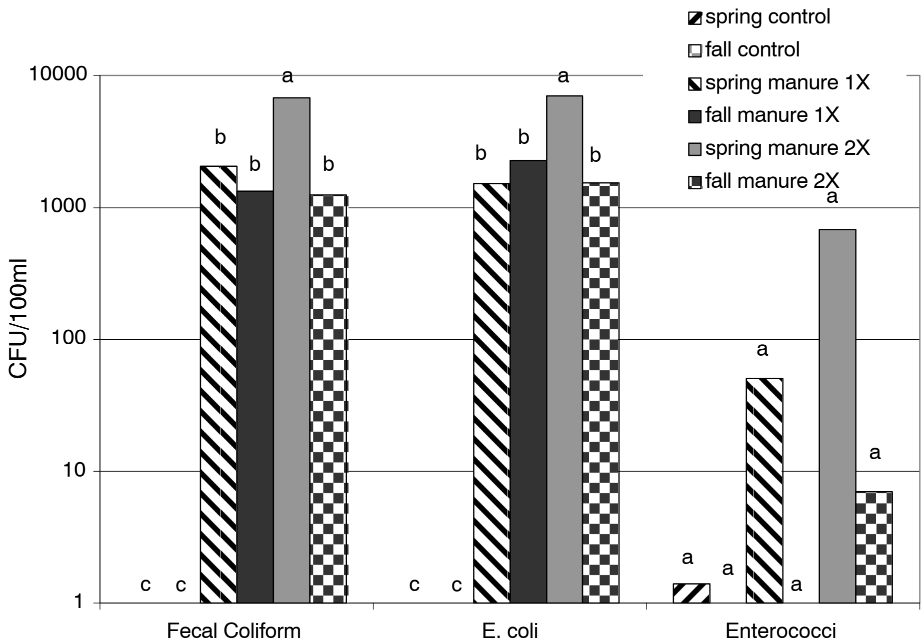

Figure 9. Bacterial densities in soil column leachate from event 4.

Enterococci are dissimilar enteric organisms, however, with a higher degree of survivability in the soil. This may explain the different pattern of enterococci levels over time and background levels of enterococci in control columns, which received no manure application. A faster decline in leachate bacterial densities in single–rate treatments can be observed in figure 5.

Generally, the double–rate manure treatment resulted in slightly higher bacterial densities in soil column leachate. This difference became more significant with successive irrigation events because of the higher organic matter present in double–rate columns. As previously noted, soil organic matter and moisture are factors that influence bacterial survivability in the soil. By buffering moisture fluctuations in the manure–holding portion of the column, organic matter may have minimized the stress of between–event drying on bacteria. Similarly, organic matter may have played a role in minimizing cellular damage due to the freeze–thaw cycle. This application rate effect was statistically significant at the 10% level for enterococci during event 3.

As in the 1998 study by Stoddard et al., generally greater bacterial leaching occurred from spring manure application versus fall manure application. The fall columns yielded similar bacterial densities as the spring columns for event one, and generally lower bacterial densities for events 2, 3, and 4. The application timing effect was significant at the 10% level during events 3 and 4 for fecal coliform, during events 2 and 3 for *E. coli*, and during event 2 for enterococci. This pattern of diverging fall and spring leachate bacterial densities over time may be the result of decreased vitality of the fall applied bacteria due to the freeze–thaw cycle. The higher organic matter available to bacteria in the double–rate columns contributed positively to the survival of bacteria. An interaction between rate and timing interaction was significant for fecal coliform during event 4 and *E. coli* during events 3 and 4. An increase in application rate resulted in a significantly greater increase in bacterial levels in spring column leachate as compared to fall column leachate.

Macropore flow, which has been previously named as a major transport mechanism for bacteria in drainage water (Smith et al., 1985), could be easily observed following irrigation and ponding. Macropores existed in every soil column and produced air bubbles during ponding.

Fluctuations in soil column gravimetric moisture content, which sometimes resulted in rapid drying, are believed to have been a major factor limiting leachate bacterial densities in this study. These fluctuations can be observed in figure 10. As discussed earlier, increased soil moisture contributes to both bacterial transport and bacterial survival in the subsurface. It is possible that more significant differences resulting from application timing and rate would be observed under more biologically ideal moisture conditions. Statistical analysis of bacterial counts yielded similar results to statistical analysis of bacterial densities, where bacterial count = Σ (bacterial density × leachate volume). There were no significant differences in drainage volume between treatments.

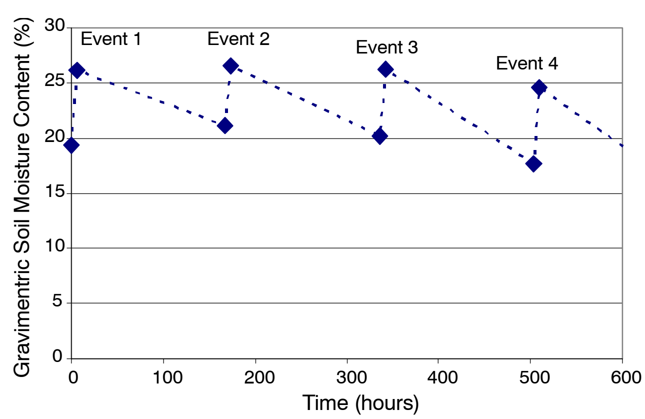

Figure 10. Average gravimetric moisture content of soil columns over time.

CONCLUSIONS

Intact soil columns were used to model the movement of bacteria (fecal coliform, *E. coli*, and enterococci) to subsurface drainage following fall and spring swine manure applications at rates of 168 kg N/ha and 336 kg N/ha. In almost every case, leachate from manured columns had significantly higher bacterial densities than leachate from non–manured control columns. This suggests that land application of swine manure may cause bacterial contamination of subsurface drain water, even at the recommended application rate of 168 kg N/ha. Clear differences in bacterial densities were identified between treatments during the second, third, and fourth irrigation events following manure application, with most significant differences occurring in the *E. coli* densities.

Spring application of swine manure resulted in higher bacterial densities in subsurface drainage than fall application during the 5–week period following spring manure application. These data are applicable where significant leaching between fall application and freeze is not likely. Specifically, the spring 336 kg N/ha treatment yielded higher bacterial densities than other treatments during the second and third irrigation events. This suggests that manure applied to the field at a rate of 336 kg N/ha during the spring may contribute significantly more bacterial contamination to groundwater and tile drainage than fall and spring 168 kg N/ha manure applications and fall 336 kg N/ha applications.

Although few significant differences were detected between application rates, the columns that received 336 kg N/ha swine manure almost always yielded higher bacterial densities in leachate than the columns that received 168 kg N/ha swine manure during the same season. Additionally, an interaction between the application rate and timing was observed, suggesting that an increase in application rate is more likely to cause greater bacterial contamination in subsurface drainage for spring application than for fall application.

As more states adopt nutrient management planning requirements, manure application guidelines are becoming an important consideration. Where manure is applied according to crop nutrient requirements, application rate is often increased in the fall to account for over–winter losses. Because of concerns associated with over–winter nutrient transport, spring application has often been favored over fall application. This study provides some insight into an important tradeoff associated with this practice. Bacterial water quality concerns must be weighed against the concerns of over–winter nutrient transport. Crop requirements in many regions of intense livestock production and low crop production are insufficient to allow for timely voiding of manure storage facilities. The increase in fall application rate necessary to meet crop requirements may allow producers to void more manure storage, and with less impact to bacterial drain water quality versus spring application.

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