Influence of Livestock Manure Type on Transport of *Escherichia coli* in Surface Runoff

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Since livestock manure type may influence transport of *Escherichia coli* (*E. coli*) in runoff, the choice of which type of livestock manure to apply to cropland may be a potential beneficial management practice (BMP) to reduce and manage *E. coli* in runoff. Four common manure types (beef, dairy, chicken, hog) were applied to a clay loam soil in small runoff boxes, and a rainfall simulator was used to generate artificial runoff. Runoff samples were collected at three successive time intervals (0 to 5, 5 to 15, 15 to 30 min) and analyzed for flow-weighted mean concentrations (FWMC) of *E. coli* as well as mass loss of *E. coli* expressed as a percentage of total *E. coli* applied. Manure treatment had a significant (*p ≤ 0.10*) influence on FWMC of *E. coli* in runoff. The FWMC of *E. coli* in runoff for the dairy (33.3 CFU per 100 mL) treatment was similar to the control (3.2 CFU per 100 mL), but *E. coli* concentrations for the beef (955 CFU per 100 mL), chicken (1,134 CFU per 100 mL), and hog (368 CFU per 100 mL) treatments were all significantly greater than the control. The FWMC values were not significantly different among the four manured treatments except for dairy versus chicken manure, where values were significantly lower for dairy manure. Concentrations of *E. coli* were less than the guideline for recreation waters (< 200 CFU per 100 mL) for the control and dairy treatment, but exceeded this guideline for beef, chicken, and hog manures, suggesting that dairy manure may be better than the other three manures for protecting surface water bodies for recreational use. Our study suggests that manure type may be a possible BMP to manage and control FWMC of *E. coli* in surface waters.

*Key words: E. coli, manure type, runoff, rainfall simulation*

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**Introduction**

Animal waste management is one type of Beneficial Management Practice (BMP) that may be used to control pollutants such as pathogens in surface runoff (Mostaghimi et al. 2001). Bacteria such as generic *E. coli* are used to indicate pollution of surface waters by pathogenic bacteria that can cause illness in humans that drink these waters or use these waters for recreation. Since livestock manure type may affect runoff of pathogenic bacteria (Crane et al. 1983; Unc and Goss 2004), manure type may have potential to be a BMP to control and manage pathogens in runoff.

The type and number of microorganisms in manure can vary with the animal species, age of animals, the type of bedding used, the method of storage (liquid or solid), and the storage period (Jamieson et al. 2002; Unc and Goss 2004). Manure properties that influence transport of *E. coli* in runoff may include the amount and nature of organic material, amount and nature of mineral material, bedding, moisture content, hydrophobicity, pH, soluble ion content, and type of soluble ions (Reddy et al. 1981; Jamieson et al. 2002; Unc and Goss 2004). When manure is incorporated into soil, interactions of the manure and soil may obscure manure property effects on transport of *E. coli* in runoff. Physical filtration is believed to be the primary process that limits bacterial mobility in soil (Gerba and Britton 1984; Maier et al. 2000). Bacteria range in size from 0.5 to 2 μm and are more subject to filtration than smaller organisms such as viruses (Maier et al. 2000). The water content of manure can influence the hydrology of infiltration and runoff, with liquid manures enhancing surface runoff and solid manures enhancing infiltration (Unc and Goss 2006).

Increasing soluble manure content generally decreases bacterial attachment in soil (Guber et al. 2005a), and has been attributed to increased competition for attachment sites (Guber et al. 2005b). The reduced attachment of bacteria to silt and clay particles in the presence of manure colloids may cause predominantly free-cell transport of manure-borne fecal coliforms in runoff (Guber et al. 2007b). The kinetics of fecal coliform release from manure was found to be similar to the release kinetics for *P* and organic *C* (Guber et al. 2006); and *E. coli* release rates changed from first-order to zero-order kinetics after 1 h of rainfall simulation (Guber et al. 2007a).

We are aware of only one study that has examined the influence of livestock manure type on runoff of generic *E. coli*. Soupir et al. (2006) applied liquid dairy manure, solid dairy manure cowpries, and solid turkey manure to a silt loam pastureland without incorporation into the soil. They used a rainfall simulator to generate artificial runoff for large (18.3 x 3 m) runoff plots under initial dry soil conditions and then under subsequent wet soil conditions. They measured flow-weighted concentrations of *E. coli* in runoff at different time intervals. The average *E. coli* concentrations in runoff for the two events were highest under cowpries (5.13 log CFU per 100 mL), followed by liquid dairy (4.26 log CFU per 100 mL), turkey (4.11 log

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CFU per 100 mL), and then the unamended control (1.15 log CFU per 100 mL). They attributed differences among the treatments to the different initial concentrations in the source material applied to their plots, which was likely due to the unincorporated manure.

We are not aware of studies that have compared the influence of manure type on runoff of E. coli when different manure sources were incorporated into the soil, which is a more realistic condition on annual cropland. In Alberta, manure applied to annual cropland has to be incorporated within 48 hours of application (Province of Alberta 2004). In southern Alberta, the dominant source of manure is from beef cattle. In addition, manure from hogs, poultry, and dairy cattle are also common. If these manure types have an influence on runoff of E. coli, the choice of manure type to be applied to cropland may be a potential BMP to manage bacteria in runoff. We are not aware of any studies that have compared the influence of these four major manure types on runoff of E. coli.

The objective of our study was to compare E. coli in runoff under beef and dairy cattle, hog, and poultry manure. Secondary objectives were to examine the influence of sampling time on E. coli in runoff, as well as the effect of solid versus liquid manure on E. coli in runoff.

Materials and Methods

Field experiments were conducted in the summer of 2006 on a clay loam Dark Brown Chernozemic soil (0- to 15-cm depth) obtained from the Lethbridge Research Center. The soil was taken from the field with a shovel, air-dried, and then sieved through a 2-mm sieve. Runoff soil boxes (100-cm length x 20-cm width x 5-cm depth) were constructed of stainless steel to hold the soil during rainfall simulations. The runoff soil boxes consisted of five individual trays to hold soil and manure for each treatment. Soil was packed into each soil tray to a bulk density of 1.10 g·cm⁻³ so that the top of the soil was level with the runoff tray.

The experimental treatments were manure applied from beef cattle, dairy cattle, chicken, and hog, as well as an unamended control. There were five replications for each of the five treatments. The solid beef cattle manure was obtained from a storage pile adjacent to the Lethbridge Research Center feedlot and consisted of feedlot pen floor manure with wood chips. The wood chip bedding was a mixture of sawdust and bark peelings derived from 80% lodgepole pine (Pinus contorta var. latifolia Engelm.) and 20% white spruce [Picea glauca (Moench) Voss]. The liquid dairy manure was obtained from a concrete storage lagoon at the dairy barns of the Lethbridge Research Center. The solid poultry manure was obtained from a local commercial poultry operation and consisted of manure and shredded newspaper. We don’t know how long the poultry manure had been stored, but its low water content (Table 1) indicated it was likely stored for a considerable length of time.

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<table>
<thead>
<tr>
<th>Manure Type</th>
<th>Application Rate of Manure (kg/ha)</th>
<th>Total N (%)</th>
<th>E. coli (log CFU/mL)</th>
<th>pH</th>
<th>EC (μS/cm)</th>
<th>SAR</th>
<th>SO4⁻ (mg/L)</th>
<th>NO₃⁻ (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beef</strong></td>
<td>26.1</td>
<td>6.4 ± 0.32</td>
<td>1.15 (±0.12)</td>
<td>6.8 ± 0.16</td>
<td>5.7 ± 0.23</td>
<td>5.8 ± 0.23</td>
<td>6.0 ± 0.11</td>
<td>6.0 ± 0.11</td>
</tr>
<tr>
<td><strong>Chicken</strong></td>
<td>6.7 ± 0.03</td>
<td>5.3 ± 0.37</td>
<td>1.10 (±0.10)</td>
<td>7.6 ± 0.27</td>
<td>6.7 ± 0.14</td>
<td>5.7 ± 0.15</td>
<td>3.4 ± 0.05</td>
<td>2.4 ± 0.05</td>
</tr>
<tr>
<td><strong>Dairy</strong></td>
<td>3.3 ± 0.03</td>
<td>5.3 ± 0.37</td>
<td>1.10 (±0.10)</td>
<td>7.6 ± 0.27</td>
<td>6.7 ± 0.14</td>
<td>5.7 ± 0.15</td>
<td>3.4 ± 0.05</td>
<td>2.4 ± 0.05</td>
</tr>
<tr>
<td><strong>Hog</strong></td>
<td>1.5 (±0.1)</td>
<td>5.3 ± 0.37</td>
<td>1.10 (±0.10)</td>
<td>7.6 ± 0.27</td>
<td>6.7 ± 0.14</td>
<td>5.7 ± 0.15</td>
<td>3.4 ± 0.05</td>
<td>2.4 ± 0.05</td>
</tr>
</tbody>
</table>

*Note: Values in parentheses are dry weight (kg) of manure applied, assuming 1 mL = 1 g.*

*EC = electrical conductivity, SAR = sodium adsorption ratio.*
Livestock Manure Type Influences E. coli in Runoff

Liquid swine manure was obtained from a storage lagoon at a local hog operation. The liquid manures in the dairy and hog lagoons were not mixed prior to collection. Manure samples were obtained in July, 2006. Solid manure samples were stored in plastic bags, and liquid manure samples were stored in 20-L plastic containers at 4°C between 4 to 17 days prior to application to the runoff boxes. Subsamples of manure were taken from the stored manure source and analyzed prior to application to each of the five replicates.

Manure was applied to soil at typical rates applied by producers in the area. The typical application rate (wet basis) for beef cattle manure to cropland in the Lethbridge area is 75 Mg·ha⁻¹ (Porcupine Coral Cleaners personal communication 2006). A similar rate was used for solid chicken manure. Typical rates for liquid dairy and swine manure in the Lethbridge area are 4,000 imperial gallons per acre or 45,000 L·ha⁻¹ (McKenzie personal communication 2006). The appropriate weight or volume of moist manure for each manure type was applied to one soil tray by hand and incorporated to a depth of 5 cm using a hand trowel. A portable Guelph rainfall simulator (Tossell et al. 1987) was used to apply deionized water to the soil trays at a rainfall intensity of 70 mm·h⁻¹. After runoff commenced, total cumulative runoff at 0 to 5, 5 to 15, and 15 to 30 min intervals was collected, and subsamples were taken for bacterial analyses. Overall, there were 5 treatments by 5 replications by 3 time intervals for a total of 75 runoff samples collected. The volume of runoff water for each of the three time intervals was measured.

Runoff water samples were analyzed for E. coli using the Colilert method (IDEXX Laboratories, Westbrook, ME, U.S.A.), and results were expressed as MPN (Most Probable Number) or CFU (Colony Forming Units) of E. coli per 100 mL of water. Manure samples were extracted with deionized water to determine the E. coli content of the water. Various manure:water ratios (1:10, 1:100, 1:1000) were used to obtain countable concentrations of E. coli. Concentrations of E. coli in manure were converted to CFU per gram of dry manure using the water content of the manure and the manure:water ratio.

The Colilert test relies on the substrates O-nitrophenyl-β-D-galactopyranoside (ONPG) and 4-methylumbelliferyl-β-D-glucuronide (MUG) to detect total coliforms and E. coli, respectively. The presence of coliforms is indicated by a change in the medium from clear to yellow, while the presence of E. coli is determined by fluorescence under long-wave (366 μm) ultraviolet light. The Colilert method has been compared with the standard membrane filtration method for various media (freshwater, soil, food, and feces) and has been found to accurately detect total coliforms and E. coli (Edberg et al. 1988; Rice et al. 1990, 1991; Clark et al. 1991; Frampton and Restaino 1993; Muirhead et al. 2004). The Colilert method for fresh water was approved by the United States Environmental Protection Agency for total coliforms in 1989, and for detection of E. coli in June 1992 (Palmer et al. 1993), and is a proposed method for total coliforms and E. coli (APHA 1998).

Flow-weighted mean concentrations (FWMC) of E. coli in runoff water were calculated by dividing the total mass of bacteria in runoff by the total volume of runoff. The mass loss of E. coli in runoff as a percentage of the total amount applied was calculated by dividing the total mass of E. coli in runoff by the total mass of E. coli applied (for each replicate), and then multiplying by 100.

The water content of the manure was determined by oven-drying a field-moist subsample of manure at 60°C, and then determining the oven-dry weight. The pH, electrical conductivity (EC), and sodium adsorption ratio (SAR) of the manure were determined on 1:5 manure and water extracts. Soluble Ca and Mg were analyzed using atomic absorption spectroscopy, and Na was determined using flame emission spectroscopy (Model AAS; PerkinElmer, Wellesley, Mass.) (Wright and Stuczynski 1996). Nitrate and ammonium in the manure were extracted using a 1:20 ratio of 10 g of manure and 200 mL of 2 M KCl after shaking at low speed for one hour. Ammonium N was determined using the Berthelot reaction on the autoanalyzer (Technicon Industrial Systems 1984). Nitrate N was determined using the copper-cadmium method (Technicon Industrial Systems 1978). Manure samples were finely ground to pass a 150-μm sieve, and total N and C were determined using the Dumas automated combustion technique (McGill and Figueiredo 1993), using a CNS analyzer (Carla Erba, Milan, Italy).

Statistical Analyses

The influence of manure type, time of sampling, and the possible two-way interaction on FWMC and mass loss of E. coli in runoff were analyzed using SAS (SAS Institute 1989). A mixed model analysis with the REPEATED statement for time of sampling was used for the analyses (Littell et al. 1998). Different covariance model types were tested to obtain the best covariance structure for the mixed model. A mixed model analysis was conducted on the log-transformed FWMC data to make the residuals normal and the variances uniform. For the percentage loss data, the data were ranked by replicate using the RANK procedure in SAS, and then the mixed model analysis was conducted on the ranked data (Conover and Iman 1981). A mixed model analysis was conducted on the untransformed runoff volume data since no log transformation was required. Comparisons among means were conducted with a Tukey-Kramer test, and were considered significant at the p ≤ 0.10 level. An ESTIMATE statement in SAS was used to determine the influence of liquid versus solid manure on FWMC, and mass loss of E. coli in runoff. Correlation analysis (p ≤ 0.05) was conducted to ascertain possible relationships between manure properties, runoff volume, and FWMC and mass loss of E. coli in runoff.
Results and Discussion

Manure Properties

Beef manure had the highest values for pH and SAR; chicken manure had the highest values for EC, total C, and total N; dairy manure had the highest values for NO$_3$-N; and hog manure had the highest values for water content, *E. coli* concentration, and NH$_4$-N (Table 1). Concentrations of *E. coli* in manure were highest for hog, followed by chicken, dairy, and then beef. Concentrations of pathogenic bacteria are likely to be greater in hog and poultry manure than in cattle manure (Unc and Goss 2004).

Mean concentrations of *E. coli* in beef manure (2.21 log CFU·g$^{-1}$ of dry manure) at the time of application after storage at 4°C for 4 to 17 days (Table 1) were considerably less than concentrations (7.61 log CFU·g$^{-1}$ of dry manure) reported in fresh pen manure taken from this same feedlot in the summer and plated within 4 hours (Miller et al. 2003). Storage of manure enhances die-off of *E. coli*, and follows simple first-order kinetics (Meals and Braun 2006). Although our manure samples were stored at 4°C to minimize die-off of *E. coli* during storage, considerable die-off can still occur at this temperature. Kuvda et al. (1998) reported that the concentration of *E. coli* 0157:H7 in cattle feces incubated at 4°C decreased by 2 logs 48 h after inoculation but remained constant thereafter. However, feedlot pen manure is often cleaned from pens and stored for periods even longer than 17 days, so storage of our manure prior to application is a common practice in the industry.

Mean concentrations (3.42 log CFU·g$^{-1}$ of dry manure) of *E. coli* in chicken manure in our study (Table 1) were comparable to concentrations (3.48 log CFU·g$^{-1}$) reported for turkey manure that was stored for three weeks (Soupir et al. 2006). Mean concentrations (3.31 log CFU·g$^{-1}$ of dry manure) of *E. coli* in dairy manure in our study (Table 1) were considerably lower than values (5.00 to 6.50 log CFU·g$^{-1}$ of dry manure) reported for fresh dairy manure by others (Guber et al. 2007a; Meals and Braun 2006; Soupir et al. 2006). Mean concentration (4.89 log CFU·g$^{-1}$ of dry manure) of *E. coli* in hog manure in our study was within the range of values (0 to 6.11 log CFU·g$^{-1}$ of dry manure) reported by Côté and Quessy (2005).

Influence of Manure Type and Sampling Time on Runoff Volume

Manure type had a significant effect on runoff volume, where values were 19 to 29% lower for chicken manure than the other four treatments (Table 2). Runoff volumes were significantly greater for each of the three successive sampling intervals (Table 2). The volume of runoff was significantly greater for liquid (2,234 mL) than solid (1,912 mL) manure, and was consistent with the higher water content of liquid than solid manures (Table 1). Liquid manure also has a higher potential than solid manure to clog finer pores in soils with no structure or macropores (Unc and Goss 2006), and may have contributed to enhanced runoff under liquid manure. We used repacked soils in our study, which had no structure and no macropores. Most field medium- to finer-textured soils have well-developed structure and contain macropores. In well-structured soils containing macropores, liquid manure favours macropore flow over matrix flow, whereas solid manure favours matrix flow over macropore flow (Unc and Goss 2006).

Influence of Manure Type and Sampling Time on Runoff of *E. coli*

The FWMC and mass loss of *E. coli* in runoff for the three sampling intervals is shown on Fig. 1. There was no significant interaction of manure type x time on *E. coli* concentration or mass loss in runoff (Table 2). In comparison, Soupir et al. (2006) reported that temporal variation of *E. coli* concentrations in rainfall simulation runoff was dependent on manure type, suggesting a possible interaction of manure type with time. However, they conducted their study on much larger (18.3 x 3 m) runoff plots than in our study, and used undisturbed field soils (silt loam) that likely had well-developed structure and macropores.
Livestock Manure Type Influences E. coli in Runoff

Manure type had a significant ($p \leq 0.10$) effect on the FWMC of E. coli in runoff (Table 2). Mean FWMC of E. coli was significantly greater for three manure-amended treatments (beef, chicken, hog) than the unamended control, indicating that application of these manures to cropland increases the potential for increased concentrations of E. coli above background levels. In contrast, mean FWMC of E. coli in runoff was not significantly different between the dairy manure treatment and the control, indicating a low potential for increased concentrations of E. coli from dairy manure above background levels compared with the other three manure types. Soupir et al. (2006) reported that average flow-weighted concentrations of E. coli in runoff from solid dairy cowpies was significantly greater than the control, but that concentrations of E. coli from unincorporated liquid dairy and turkey amended fields were similar to the control.

For comparisons among the four amended treatments (Table 2), mean FWMC of E. coli were similar among all two-way comparisons except between dairy and chicken, where concentrations were significantly greater for the chicken than dairy treatment. Soupir et al. (2006) reported contrasting results where they found no significant difference in average flow-weighted concentrations of E. coli in runoff between turkey and liquid dairy manure treatments. They also reported that E. coli concentrations were significantly greater under solid dairy cowpies than turkey litter, and there was no difference between solid dairy cowpies and liquid dairy manure.

Mean FWMC values of E. coli in runoff for the control and dairy treatment (Table 2) were less than the water quality guideline ($<200$ CFU per 100 mL) for recreational waters (Health Canada 1992). In contrast, mean FWMC values exceeded this guideline by 5.7 times for chicken manure, 4.8 times for beef manure, and 1.8 times for hog manure. Therefore, our results suggest that dairy manure application may be the best BMP for maintaining surface water quality for recreational use with respect to E. coli. In comparison, concentrations of E. coli in runoff from liquid dairy, solid dairy cowpies, and solid turkey litter in the study by Soupir et al. (2006) were $>200$ CFU per 100 mL, whereas runoff from the control plots was below this value.

Manure treatment had no significant effect on mass loss of E. coli in runoff (Table 2). The percentage of applied E. coli lost in runoff ranged from 0.1 to 5.3%.

### Table 2. Influence of manure treatment, sampling time, and manure type (liquid vs solid) on flow-weighted mean concentration (FWMC) of E. coli, loss of E. coli in runoff as a percentage of applied, and on volume of runoff

<table>
<thead>
<tr>
<th>Treatment</th>
<th>FWMC of E. coli in runoff (CFU per 100 mL)</th>
<th>Mass loss of E. coli in runoff (%)</th>
<th>Volume of runoff (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check</td>
<td>3.2±1.3 c</td>
<td>—</td>
<td>2123±320 a</td>
</tr>
<tr>
<td>Dairy</td>
<td>33.3±9.1 bc</td>
<td>0.5±0.2 a</td>
<td>2248±334 a</td>
</tr>
<tr>
<td>Beef</td>
<td>955±298 ab</td>
<td>5.3±4.5 a</td>
<td>2077±272 a</td>
</tr>
<tr>
<td>Chicken</td>
<td>1134±578 a</td>
<td>0.7±0.4 a</td>
<td>1747±282 b</td>
</tr>
<tr>
<td>Hog</td>
<td>368±86.8 ab</td>
<td>0.1±0.03 a</td>
<td>2221±327 a</td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–5 min</td>
<td>482±159 a</td>
<td>0.2±0.1 b</td>
<td>783±44.9 c</td>
</tr>
<tr>
<td>5–15 min</td>
<td>791±389 a</td>
<td>0.8±0.3 a</td>
<td>2054±56.4 b</td>
</tr>
<tr>
<td>15–30 min</td>
<td>300±163 b</td>
<td>3.8±3.2 ab</td>
<td>3373±99.6 a</td>
</tr>
<tr>
<td>Liquid</td>
<td>200±55.1 a</td>
<td>0.3±0.1 a</td>
<td>2234±229 a</td>
</tr>
<tr>
<td>Solid</td>
<td>1045±320 a</td>
<td>2.8±2.1 a</td>
<td>1912±195 b</td>
</tr>
<tr>
<td>Treatment</td>
<td>&lt;0.0001 †</td>
<td>0.2278</td>
<td>0.0080</td>
</tr>
<tr>
<td>Time</td>
<td>0.0082</td>
<td>0.0059</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Treatment x Time</td>
<td>0.2688</td>
<td>0.4221</td>
<td>0.2443</td>
</tr>
<tr>
<td>Liquid vs Solid</td>
<td>0.2679</td>
<td>0.3399</td>
<td>0.0030</td>
</tr>
</tbody>
</table>

*Mean ± standard errors followed by different lower case letters (by column) are significantly different at $p \leq 0.10$.
†Probability ($p$) of F statistic occurring by chance. Values $\leq 0.10$ indicate a significant effect.
Other researchers have reported annual mass losses for fecal coliforms in runoff from manured land ranging from 2 to 23% (Robbins et al. 1971), 0.1% (McCaskey et al. 1971), 0.1 to 6.7% (Kunkle 1979), and 0.1 to 90% (Crane et al. 1983). Percentage losses of fecal coliforms in runoff were generally highest immediately after application, and decreased dramatically with increased residence time of manure in the soil. Overall, our ranges in mass losses were within the range of values reported by others.

Although there was no significant difference between solid and liquid manure for mean FWMC and mass loss of *E. coli* in runoff (Table 2), the nonsignificant trend was for higher *E. coli* in runoff under solid than liquid manure. McCaskey et al. (1971) also reported that mass loss of fecal coliforms was greater for solid than liquid dairy manures. In comparison, Soupir et al. (2006) reported no significant difference in concentrations of *E. coli* in runoff between liquid dairy manure, solid dairy manure, and solid turkey manure. Since liquid manure favours runoff over infiltration and solid manure favours infiltration over runoff (Unc and Goss 2004, 2006), higher *E. coli* in runoff would be expected under liquid than solid manure if simply based on hydrological partitioning. However, other physical-chemical factors such as bacterial attachment, filtration, mechanical filtration (Guber et al. 2005a), and other factors may also be important in influencing *E. coli* in runoff under liquid and solid manure application.

Sampling time had a significant effect on FWMC and mass loss of *E. coli* in runoff (Table 2), and was consistent with previous findings reporting that time dependent processes are important in the transfer of bacteria from soil to runoff (Crane et al. 1983). Peak values occurred at the second (5 to 15 min) sampling interval for FWMC, and at the third (15 to 30 min) sampling interval for percentage loss of *E. coli*, and may be related to gradual dissolution of manure lumps and delayed release of *E. coli*. Soupir et al. (2006) examined the temporal distribution of *E. coli* in runoff over 3 h for dry soil conditions, and over 1 h for wet soil conditions. They found that peak *E. coli* concentrations were the highest for the first sampling interval, or else concentrations increased with time as runoff intensity increased and peak concentrations occurred at later sampling intervals. Correlation analyses of the volume of runoff versus concentration of *E. coli* in runoff for each manure type and replicate and time interval indicated no significant relationships between runoff volume and *E. coli* in our study. Guber et al. (2007a) reported that dilution and loss to infiltration were the dominant mechanisms causing a decrease in *E. coli* during runoff.

To determine any potential influence of manure properties on runoff of *E. coli*, correlations were conducted between FWMC and mass loss of *E. coli* in runoff versus selected manure properties such as *E. coli* concentration in manure, mass of *E. coli* applied in manure, water content of manure, pH, EC, SAR, total N, total C, NH₄-N, and NO₃-N. No significant (*p > 0.05) relationships were found among any of the correlations (data not shown), suggesting none of these manure properties influenced *E. coli* in runoff. However, the absence of any relationships may have also been due to the small (*n* = 4) sample size used for correlation analyses.

The greater the concentration of bacterial pathogens in manure, the more likely some will be transported (Goss et al. 2002). The *E. coli* concentration in manure followed the sequence: hog>chicken>beef>dairy. The *E. coli* concentration in runoff followed the sequence: chicken>beef>hog>dairy. If *E. coli* in runoff was simply related to the concentration of *E. coli* in the original source material, then *E. coli* in runoff should have been highest for hog manure, and followed the above sequence that we found in manure. Since this did not occur and there was no significant correlation between *E. coli* in manure and *E. coli* in runoff, we concluded that *E. coli* in runoff was not related to concentrations in the manure, and that interactions of the manure with soil upon incorporation may have obscured this effect. In contrast, Soupir et al. (2006) reported that *E. coli* concentrations in runoff were primarily due to the different initial bacterial concentrations in the source manure applied to their plots. However, they did not incorporate the manures into the soil in their study (and we did), which may account for them finding a link between *E. coli* in runoff and source manure.

We are unsure as to why manure type had a significant influence on FWMC of *E. coli* in runoff but had no affect on mass loss of *E. coli* (Table 2), and further research is required to investigate the mechanisms involved. Manure is a heterogeneous complex mixture containing water, soluble inorganic and organic chemicals, soil, microorganisms, and dietary fibre. Previous research has shown that increased dissolved manure content resulted in decreased attachment of *E. coli* to soil (Guber et al. 2005a, 2005b), particularly to those soils with high silt, clay, and coated sand fractions, and this may enhance free-cell transport of manure-borne *E. coli* in runoff (Guber et al. 2007b). We found a nonsignificant (*p = 0.06) but strong positive correlation (*r = 0.94*) between the dry weight of manure applied (Table 1) and FWMC of *E. coli* (Table 2), suggesting that increasing solid manure content may contribute to greater *E. coli* concentrations in runoff. The decrease in bacterial attachment in the presence of manure may be caused by modification of soil mineral surfaces by soluble organic and inorganic constituents in manure, adsorption of bacteria on manure particulates, competition of dissolved organic matter and bacteria for adsorption sites, or bacterial surfaces being modified by dissolved organic matter (Guber et al. 2005a).

**Conclusions**

Both concentration and mass loss data are required to evaluate nonpoint source pollution (Magette 2001).
Conover WJ, Iman RL. 1981. Rank transformations as significantly greater than the control. Therefore, dairy for the beef, chicken, and hog treatments were all than the unamended control, but dairy manure application was not significantly greater percentage of applied. The FWMC of on concentrations and mass loss of E. coli in runoff. Our study evaluated the influence of manure type on concentrations and mass loss of E. coli in runoff. Manure type had a significant influence on FWMC of E. coli in runoff, but not on mass loss of E. coli as a percentage of applied. The FWMC of E. coli under dairy manure application was not significantly greater than the unamended control, but E. coli concentrations for the beef, chicken, and hog treatments were all significantly greater than the control. Therefore, dairy manure may not increase E. coli concentrations in runoff above background levels, whereas beef, chicken, and hog manure may increase E. coli concentrations above background levels. For the two-way comparisons among the amended treatments, FWMC of E. coli were similar among all comparisons, except where concentrations were greater for chicken than dairy. Concentrations of E. coli were less than the guideline for recreation waters (<200 CFU per 100 mL) for the control and dairy treatment, but exceeded this guideline for beef, chicken, and hog manures, suggesting that dairy manure may be better than the other three manures for protecting surface water bodies for recreational use. Therefore, applying dairy manure instead of beef, chicken, and hog manure type may be a potential BMP to manage E. coli concentrations in runoff. Further research is required to study the influence of manure type on runoff of E. coli at the field scale using undisturbed and structured soils containing macropores.

Acknowledgments

Field and laboratory assistance was provided by Caylee Dyck, and statistical advice by Toby Entz. The constructive comments by two anonymous reviewers greatly improved this manuscript.

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Received: 27 September 2007; accepted: 2 May 2008.