Transport of bacteria from manure and protection of water resources

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Accepted 13 August 2003

Abstract
Survival and transport of pathogens from manure in the environment depend on a number of complex phenomena. An important question is how the properties of such a complex environment as the soil–manure medium impact the persistence of bacteria within the vadose zone. First, manure can change the partitioning of precipitation water between infiltration (enhanced by solid manure) and surface runoff (stimulated by liquid manure). Components of manure, such as straw and coarse organic matter, can strain and filter micro-organisms from the transporting water. After infiltrating the soil, the retention of bacteria depends on the physical configuration of soil, the soil chemistry, and the properties of the microbial cells. Transport of bacteria in soils obeys the general laws pertinent to macropore flow and the interaction between particles and surfaces of variable charge. Detailed characterisation of the variable properties within the structured soil profile is a difficult task. Application of manure can result in significant changes in the physical and electrochemical properties of the soils and microbial cells. Such changes can affect the interaction between bacterial cells and soils in several ways: increase filtration, modify the kinetics of the physico-chemical interactions between charged surfaces, and alter the competition for retention sites between suspended soluble and particulate compounds. Survival of faecal bacteria is affected by the physical and chemical conditions existing prior to manure application as well as by conditions imposed by mixing soil and manure. Competitive interaction with native soil bacteria, in the soil–manure mixtures, is an important aspect governing survival of introduced organisms.

1. Introduction
In the Walkerton (Ontario, Canada) tragedy of May 2000, contamination of the municipal water system with Escherichia coli O157:H7 and Campylobacter jejuni resulted in 2300 people requiring medical attention, 7 of whom died. This is a community that has a population of only about 5000 people. The total cost attributable to the Walkerton water crisis was estimated at US$ 64.5 million (Livernois, 2002). Investigation into the causes of the microbial contamination of the municipal well water, the common source for those affected, indicated that the most likely cause was transport of manure bacteria to the aquifer by infiltrating water, although direct entry of surface runoff into the well could not be ruled out (O’Connor, 2002). This tragic event showed that even under current best manure management practices, contamination of water resources with micro-organisms can occur and have a

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catastrophic impact on public health if other barriers to the spread of disease in piped water supplies are inadequately enforced.

Reports have indicated greater occurrence of contamination of ground water with nitrate in areas where animal manure is applied regularly. However, the overall impact of agricultural land use practices on regional ground water quality is not well understood (Goss et al., 1998). The Ontario Farm Groundwater Quality Survey found that the proportion of wells contaminated with faecal bacteria was significantly greater on farms where manure was spread than where only mineral fertiliser was used (Goss et al., 1998), pointing to manure use on farms as a significant source of well water contamination for both nitrate and bacteria. The bacterial groups present in greatest number in manure are faecal coliforms and streptococci, with Salmonella spp. also being found occasionally (Table 1).

The concentration of a given micro-organisms in manure applied to soil is an important parameter determining the potential for contamination of water resources. The greater the concentration, the more likely it is that some will be transported (Goss et al., 2002). The type and number of micro-organisms 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 (Lachica, 1990; Nodar et al., 1992). Given the many possibilities for handling manure on farms, the opportunity to modify the source strength of the pathogens as well as the form of the material that may gain access to the wider environment, guidelines for farmers are important for limiting the negative impact of agricultural activities on the water resources. However, appropriate recommendations for manure management to protect water resources from pathogens cannot be formulated without a detailed understanding of the factors affecting the survival and transport of micro-organisms from manure between source locations and surface or groundwater bodies.

Studies on the transport of faecal bacteria from manure through soil have concentrated on their potential to travel through soil and reach an aquifer or enter drainage tiles eventually moving to surface water courses (e.g. Culley and Phillips, 1982; MacLean et al., 1983; Patni et al., 1985; Shrestha et al., 1997; Conboy, 1998; Joy et al., 1998), or the evaluation of management procedures that influence the contaminant potential of manure micro-organisms, including research on the changes in bacterial numbers during manure storage and handling (Sutton, 1983; Lachica, 1990; Nodar et al., 1992; McMurry et al., 1998), the survival of faecal bacteria in the environment (e.g. Fenlon, 2000), the accidental contaminant potential due to point sources of contamination, and the impact of the soil management on the contaminant potential of manure bacteria (e.g. Cook et al., 1997; Stoddard et al., 1998). On the other hand, detailed investigations of the impact of cell properties on transport have been performed mostly under conditions of reduced ionic strength and low colloidal concentrations (Marshall, 1985; Stenström, 1989; Gannon et al., 1991a,b; Huysman and Verstraete, 1993).

Although the contaminant potential of manure bacteria is recognised and the properties that are important for the transport of these micro-organisms through soil have been identified (Gerba and Bitton, 1984; Slotzsky, 1985; Abu-Ashour et al., 1994; Mawdsley et al., 1995), there is a lack of specific information on how manure influences the expression of these properties. Furthermore, there is little information on how the variable expression of bacterial cell surface properties affects retention within soil and manured soil. These are important questions for quantifying the risks associated with faecal pathogens since they originate in manure and in many cases enter the wider environment when applied to agricultural fields with the manure. The long-term effects of addition of manure on the increases in soil organic matter content and therefore on the soil structural stability are well known (e.g. Tester, 1990). While these effects are also important for the transport of manure bacteria through soil there is no information available on the short-term impact of different manure types on the soil properties relevant to bacterial transport.
Table 1
Examples of bacterial numbers in some animal manure (CFU ml$^{-1}$ or g$^{-1}$ fresh manure)

<table>
<thead>
<tr>
<th>Manure type</th>
<th>Faecal coliforms</th>
<th>Faecal streptococci</th>
<th>Salmonella spp.</th>
<th>Protozoa and others</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid swine manure</td>
<td>$4.3 \times 10^3$ to $1.3 \times 10^5$</td>
<td>$9.3 \times 10^3$</td>
<td>0</td>
<td></td>
<td>Unc (1999)</td>
</tr>
<tr>
<td></td>
<td>$2.4 \times 10^2$</td>
<td></td>
<td></td>
<td></td>
<td>Weigel (1995)</td>
</tr>
<tr>
<td></td>
<td>$9.5 \times 10^2$ to $1.1 \times 10^4$</td>
<td>$7.2 \times 10^2$ to $4.5 \times 10^3$</td>
<td>$0$ to $1.5 \times 10^3$</td>
<td>(streplicocci-D)</td>
<td>Rüppich (1994)</td>
</tr>
<tr>
<td>Liquid cattle manure</td>
<td>$2.4 \times 10^3$</td>
<td>$9.3 \times 10^3$</td>
<td>0</td>
<td></td>
<td>Weigel (1995)</td>
</tr>
<tr>
<td></td>
<td>$4.5 \times 10^2$ to $1.5 \times 10^6$</td>
<td>$4.5 \times 10^2$ to $9.5 \times 10^3$</td>
<td>0</td>
<td></td>
<td>Rüppich (1994)</td>
</tr>
<tr>
<td>Dairy slurry</td>
<td>$6.3 \times 10^5$ to $1.0 \times 10^7$ (enterobacteria)</td>
<td>$4.7 \times 10^5$</td>
<td>2.7 $\times 10^7$</td>
<td></td>
<td>Östling and Lindgreen (1991), and Crane et al. (1983)</td>
</tr>
<tr>
<td></td>
<td>$2.4 \times 10^2$ (E. coli)</td>
<td>$1.5 \times 10^3$</td>
<td>0</td>
<td></td>
<td>Weigel (1995)</td>
</tr>
<tr>
<td>Solid beef manure</td>
<td>$2.4 \times 10^3$</td>
<td>$1.5 \times 10^3$</td>
<td>0</td>
<td></td>
<td>Unc (1999)</td>
</tr>
<tr>
<td></td>
<td>$1.9 \times 10^3$ to $6.8 \times 10^6$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid dairy manure</td>
<td>$2.0 \times 10^5$ to $1.0 \times 10^7$ (enterobacteria)</td>
<td></td>
<td></td>
<td></td>
<td>Östling and Lindgreen (1991)</td>
</tr>
<tr>
<td>Fresh cow manure</td>
<td>Up to $1.0 \times 10^9$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheep</td>
<td>$6.0 \times 10^6$</td>
<td>$6.6 \times 10^7$</td>
<td></td>
<td></td>
<td>Crane et al. (1983)</td>
</tr>
<tr>
<td>Horse</td>
<td>$9.4 \times 10^6$</td>
<td>$6.5 \times 10^7$</td>
<td></td>
<td></td>
<td>Crane et al. (1983)</td>
</tr>
<tr>
<td>Poultry</td>
<td>$1.3 \times 10^9$ to $1.4 \times 10^9$</td>
<td>$6.2 \times 10^5$ to $9.7 \times 10^8$</td>
<td></td>
<td></td>
<td>Crane et al. (1983)</td>
</tr>
</tbody>
</table>

From $2.5$ to $1.8 \times 10^9$ in healthy animals to $1 \times 10^8$ in sick animals

(Cryptosporidium parvum)

Mawdsley et al. (1995), Clinton et al. (1979), Scott et al. (1994), and Smith (1992)
The purpose of this review is to indicate recent developments in understanding microbial transport, especially that through the vadose zone, and to highlight the research gaps that limit the advice available on manure management to ensure the protection of water resources.

2. Survival of micro-organisms from manure in soil

Survival rate of micro-organisms introduced into the soil is an important factor influencing their potential to contaminate water resources. The survival conditions for the enteric bacteria once voided from the animal organisms are considered unfavourable. Nevertheless, some can survive for extended periods, at least up to sixty days (Fenlon et al., 2000), or in what are considered least hospitable environments such as on fabrics and plastics (Neely, 2000; Robine et al., 2000). Antibiotic resistant strains of *E. coli* and *Streptococcus faecalis* were found to persist in high numbers over a period of at least 32 days in saturated soil conditions (Hagedorn et al., 1978). Recent research shows that *E. coli* and *Enterococcus* spp. from pig manure may survive in soil for even longer periods—40–68 days after application (Shreshta et al., 1997; Cools, 2001).

The survival rate of bacteria in soil depends on the source, microbial species and on the manure application method (Rüprich, 1994). During the storage of liquid manure the population of viable organisms initially declines rapidly only to regain numbers later, in one example up to five-fold the initial value after 14 weeks (Nodar et al., 1992). There are gradients of temperature within a completed solid manure pile, which are the result of different rates and types of organic matter digestion (from aerobic at the periphery, to more anaerobic toward the centre of the pile). Micro-organisms have different rates of survival in these zones. The ones near the periphery have more chances to survive and form sources of contamination (Sutton, 1983).

The amount of pathogenic bacteria is likely to be greater in swine and poultry manure than in cattle manure. Due to the greater mobility of bacteria in the liquid phase compared to the solid phase, liquid manure tends to be more uniformly contaminated than does solid manure. Pathogens may be found in manure even if the animals present no symptoms (Goss et al., 2002). While manure samples from individual animals may not be contaminated, a supply of manure from storage can contain pathogens that have been shed by a restricted number of animals (Busato et al., 1999; Strausch, 1988), thus the greater the number of animals on a farm the greater the chances for pathogens to be found in manure.

Methods for the land application of manure depend on the manure type (liquid or solid), soil type, and crop type (Goss et al., 2002). When manure is injected into soil, micro-organisms are less likely to be destroyed by the ultraviolet solar radiation than if the manure remains on the soil surface. On the other hand, incorporation by injection increases the possibility for micro-organisms to be adsorbed onto soil particles (Patti, 1985). The normal tillage used in farming operations can influence the conditions that microbes from manure experience after application. For example, biological activity near the soil surface is greater in no-till than in conventional tillage, which results in better conditions for survival of the indigenous soil micro-organisms (Levanon et al., 1994). Addition of manure results in increased availability of carbon substrates and mineral nutrients that in turn boost the soil biological activity. Significant mineral nutrients in manure include ammonium ions, phosphate, potassium, sodium, magnesium and calcium; metals such as zinc and copper. The level of available nutrients in the soil modifies survival rate of bacteria (Rattray et al., 1992). Tenuta and Lazarovits (2002) found that ammonia, nitrous acid and fatty acid toxicity following application of nitrogen rich organic amendments can kill microsclerotia of plant pathogens present in soil. Thus, the high level of aqueous ammonia in liquid manure may be toxic to microbial populations. Survival of faecal coliforms is greatly extended in organic soil compared with that in mineral soils. This might have to do with the higher water-holding capacity level of these soils (Gerba and Bitton, 1984). However, laboratory tests performed by Cuthbert et al. (1950), showed that *E. coli* and faecal streptococci survive several weeks in limestone (pH 5.8–7.8) while dying in a few days in a peat soil (pH 2.9–4.5), indicating the importance of pH as well as water content. Bacteria are considered to be more likely to survive a longer period in soils with high water-holding capacity (Gerba and Bitton, 1984). Low matric potentials—large negative
values—are associated with dry conditions and reduced viability of bacterial cells in soil (Sjogren, 1994). In the soil, cool temperatures favour faecal bacteria survival. Stress induced by starvation, low temperatures, and low levels of available water can reduce the microbial metabolisms, phenomenon observed as viable but not culturable bacteria (Colwell, 1993; Chmielewsky and Frank, 1995; Bogosian et al., 1996). This means that although bacteria are viable, and potentially pathogenic, they cannot be readily grown on identification substrata. However, even partial changes in the environment, such as increased temperature, can lead to reactivation and accelerated multiplication of such cells (Jiang and Chai, 1996).

The increase in nutrients engendered by the addition of manure may also result in an increase of the predatory population. Competition between soil organisms has been found to be a major factor in the reduction of the bacterial populations introduced in soils (Acea et al., 1988; Recorbet et al., 1992; Soda et al., 1998). Murray and Hinckley (1992) found that the number of Salmonella enteritidis is more limited in the presence of earthworms (Eisenia fetida)—8% reduction versus only 2% reduction without earthworms. Normal soil bacterial flora was also reduced in the presence of earthworms. Other soil micro-organisms such as protozoa, nematodes and Bdellovibrio—a soil bacterium—prey on soil bacteria and implicitly on the ones introduced with manure (Goss et al., 1996). Aggregation of cells triggered by various stress factors, and nutrient gradients can increase bacterial resistance to unfavourable conditions in the environment (Bossier and Verstraete, 1996). The survival of faecal bacteria can extend over long periods after manure application and once bacteria reach the ground water the survival period can be extended to several months (Goss et al., 1996). Sjogren and Gibson (1981) indicated that faecal bacteria survive even in very dilute mediums such as lake waters.

3. Manure components that can affect the microbial contaminant potential of manure

In addition to bacteria, which are the focus of this review, manure contains mineral nutrients and organic compounds, including endocrine disrupting substances and antibiotics, that can influence humans as well as other organisms, and the complex breakdown products resulting from digestion of plant material and the by-products of animal metabolism. The carbon content and the forms of carbon vary between manure sources with the proportion of each carbon compound type varying during storage (Eneji et al., 2001). In solid manure there is considerable addition of bedding material, but most manure contains fibrous material. The manure of non-ruminants will tend to contain more cellulose compounds, while the manure of ruminants will have a higher bacterial content because of their production in the substrate-rich rumen (MacLean et al., 1983). The carbon content of manure can be correlated with its dry matter content. Hence, liquid manures contain a smaller amount of carbon per unit fresh weight than do solid manures. Although, liquid manures tend to contain fewer bacteria per unit fresh weight, there are no significant differences in the number of bacteria per unit dry matter, and thus carbon content (Unc, 1999). The higher level of ammonium combined with a smaller carbon content in the liquid manure results in an environment where N is abundant. Potter et al. (2001) found the C:N ratio of liquid manure to be about 1:11. This still results in an environment where it is generally considered that C, rather than N, is the limiting factor for bacterial growth. Nevertheless, much of the carbon in manure is readily available to micro-organisms, so that when manure is released into watercourses decomposition results in a large demand for oxygen. Swine manure has a very high biological oxygen demand (BOD), ranging between 70,000 and 200,000 mg l$^{-1}$ (ASAE, 1998). Such observations cast doubt on whether carbon is limiting in manure or whether it is the build-up of toxic components that limits microbial activity.

An important feature of the carbon compounds in manure is that they are a source of both soluble and insoluble colloidal material (Giusquiani et al., 1998; Gregorich et al., 1998). Elemental analysis, acidic functional group determination, E4/E6 ratio, gel-filtration chromatography and magnetic resonance spectroscopy analysis of acid soluble and acid insoluble dissolved organic carbon from pig slurry, organic wastes and humic and fulvic acids from soils showed similarities between sources (Giusquiani et al., 1998).

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Carboxylic groups present on the surface of dissolved organic matter from pig slurry conferred a complexing capacity similar to humic acids from a clay-loam soil (Businelli et al., 1999).

The electrical conductivity (EC) of leachate from manure indicates the presence of free charges. The charges are mostly due to the presence of K\(^{+}\), Cl\(^{-}\), Na\(^{+}\), and NH\(_4\)\(^{+}\). Fewer ions enter the soil after application of solid manure than after liquid manure. The latter has an equivalent ionic concentration of about 0.1 M (Table 2). Leachates from piles of fresh dairy manure have an EC value similar to that of liquid manure. Feedlot runoff may have an EC of about 4–6 mS cm\(^{-1}\) (Sweeten, 1998). The EC of manures increases with time during the first 200 days of storage after which it declines slightly (Eneji et al., 2001).

As indicated in Section 2, the organic and inorganic components of manure have an impact on the survival of bacteria, and hence their potential for transport. The presence of charged ions in solution can modify the properties of both soil and microbial surfaces (see Section 4), altering the potential for the adsorption of microbes onto the soil. Fibrous organic matter will encourage straining and filtration of microbes from infiltrating liquid. Other organic carbon components can alter the electrochemical properties of microbial surfaces and thereby influence the likelihood that the microbes will remain in the pore water (Section 4).

### 4. Transport of water and micro-organisms from manure

Although bacteria from manure are known to enter water resources (Goss et al., 2002) and numerous studies indicate the potential for microbial contamination from manure sources (Joy et al., 1998; Stoddard et al., 1998; Unc, 1999), there has been little progress in the way of direct analysis of the physical and chemical interactions between the manure type and bacteria that may affect the potential for contaminating water resources. Transport and retention of particulates, such as bacterial cells, in the soil is recognised as being a very complex physical and chemical phenomenon dependent on the interaction of the various complex properties of soil, cells and suspending solutions. Four major factors have been identified that influence the movement of bacteria through the soil (Fontes et al., 1991; Gannon et al., 1991a): (1) flow characteristics, which depend on the grain size of the porous medium, and on the soil structure that combined control the active porosity. We include the partitioning of the water at the soil surface into runoff and infiltration as a major aspect of this factor in bacterial movement. (2) Filtration effects due to soil micropores, clogging in macropores necks, and filtration pads formed by solid components from applied manure (solid manure mostly) as a function of the size of microbial cell. (3) Straining within organic materials pads formed on soil surface, which is the sum of the filtration and the electrochemical retention to organic surfaces within the organic pads on soil surface. (4) Retention of bacterial cells on soil mineral and organic particles by adsorption and adhesion, with the ionic strength of the soil solution playing an important role. Retention is the resultant of complex interactions between components of bacterial cells, soils and soil suspending solution.

#### 4.1. Flow characteristics and water partitioning at soil surface: general considerations

Transport of bacteria is mostly passive, being determined by the presence of rapid water fluxes, although...
cell motility can play a significant role in movement in suspension over short distances. Therefore, the path followed by water, infiltration or surface runoff determines the direction of transport of bacteria from a source. Partitioning of rainfall or irrigation waters into infiltration and runoff is a function of the soil hydraulic properties, soil cover, slope, and the characteristics of the precipitation. Accordingly, this partitioning of the precipitation water is the main factor that determines the resource that is at risk of contamination (surface water or groundwater) and the rate at which the bacteria will move from the source.

There is evidence that bacterial transport in the vadose zone may occur very rapidly in any field that receives water at a sufficient rate to fill the soil pores (McMurry et al., 1998; Unc and Goss, 2003). Water can move downwards through the soil profile faster than expected from estimates of the hydraulic conductivity of the soil matrix due to the preferential (bypass) flow paths that avoid the soil matrix (Jury and Flühler, 1992; Unc and Goss, 2003). These flow paths are commonly equated with soil macropores. Experimental results indicate that bypass flow is the rule rather than the exception in most structured soils (Simpson and Cunningham, 1982; Singh and Kanwar, 1991; Flury et al., 1994). This type of flow may give contaminants a more direct and rapid path to groundwater (Goss et al., 2002; Unc and Goss, 2003). There is little agreement between researchers as to how macropores are defined. Thus, the minimum size of soil pores defined as macropores can vary from >30 μm to >3000 μm (Beven and Germann, 1981). Under certain conditions, flow-bypassing of the soil matrix may take place within capillary-sized pores (Beven and Germann, 1982) or within vertical zones of loose, porous, fine structured soil through which rapid saturated flow occurs, phenomenon known as fingering (Simpson and Cunningham, 1982; Kung, 1990). Nevertheless, particulate materials move through soil, carried by infiltrated waters, through pores of a size that allows their passage. Only the pores that are several times larger than the dimensions of the particulate allow transport over significant distances. Consequently particulates, such as micro-organisms, travel only through the larger pores where the water flux reaches peak velocities. As a result particulates may be transported rapidly, in a suspended state, over a distance determined by the extent to which macropores are continuous (Jacobsen et al., 1997) and thus the extent of preferential flow has a direct influence on the depth to which particulates can be moved. In general, experimental work has shown no clear effect of the initial soil water content, or water potential gradient on the flow pattern through structured soils and the maximum penetration depth of the water. In some cases, greater preferential flow has been observed in wet soils (Flury et al., 1994). However, even if the mechanisms that create preferential flow are relatively well understood, the development of preferential flow cannot be predicted exactly from the commonly measured physical characteristics of soil.

Soil erosion–control practices have been developed to favour infiltration over runoff, and consequently infiltration tends to have increased importance in properly managed fields. The infiltration rate of water following a rain is often limited by the formation of a soil crust that has a hydraulic conductivity of several orders of magnitude less than that of the soil profile (Morin et al., 1981). Seal formation on a bare soil depends on the kinetic properties of the raindrop in the context of the physico-chemical properties of the soil. The permeability of the seal rather than that of the underlying layer determines the equilibrium infiltration rate for the soil (Shainberg et al., 1997). The decrease in flux through the crust can create conditions for unsaturated flow in the soil profile underneath (Morin et al., 1981). The associated reduction in soil surface hydraulic conductivity can increase the runoff potential as the rainfall intensity will then be greater than the infiltration rate.

4.1.1. Potential impact of manure on flow characteristics and water partitioning at soil surface

The presence of ions with a greater hydration shell at the surface of clay particles favours chemical dispersion of clay particles. As the exchangeable sodium potential at the soil surface increases relative to Ca\(^{2+}\), the raindrop impact energy required to cause seal formation is reduced (Shainberg and Singer, 1988; Keren, 1990). Manure application, especially liquid manure, results in increased ionic concentration at the soil surface. Long-term application of manure high in salts can increase the amount of Na\(^{+}\) that is exchanged with Ca\(^{2+}\) in soil favouring enhanced chemical clay dispersion. On the other hand, if few Na\(^{+}\) ions are within
the soil aggregates at the moment of manure application, the Na\(^+\) in manure probably has a less immediate effect. On the contrary, the main effect in such a situation would be aggregation as the electric double layers are compressed at the increased ionic concentration of the manure solution.

A change in pH is another factor that should be considered when manure liquids are applied as the clay is more likely to be dispersed by water as soil departs from its electrical point of zero charge (Gillman, 1974). Application of liquid manure with little dry matter content wets the soil surface. If rain occurs before the soil dries, even if the kinetic energy of raindrops is reduced, soil aggregates are more likely to disintegrate and the water dispersible clay can seal the smaller soil pores.

A cover of manure containing significant amounts of bedding material can reduce the effect of the kinetic energy of rain on soil surfaces and limit formation of soil surface seals by decreasing the water potential at the soil surface and by preventing ponded conditions. By limiting pore occlusion at the soil surface, there is a greater likelihood that colloidal particles and bacteria will move below the soil surface. However, it is not known how migration of dispersed clay particles from the bare soil surface in the spaces between the manure aggregates participates in the overall seal formation. Unc (1999) showed that immediate infiltration rates were less reduced after application of solid manure than after application of liquid manure. The formation of a seal following application of liquid manure, soil saturation, and subsequent ponding of water, were given as possible causes. The increased water-absorptive capacity of the bedding material (Barry, 1999) in solid manure could also have been a factor, in that it would reduce the hydraulic potential at the soil surface and thereby alter the water partitioning.

Application of manure may well induce a sealing effect at the soil surface, independently of the soil seal formation. Barrington and Jutras (1983) noted that when swine and dairy slurry was applied to soil, two zones of filtration were established, one within the solid mat, which accumulated at the soil surface and the second at the soil–manure interface. Infiltration rates were reduced to a greater extent by the application of dairy slurry than pig slurry (Barrington and Jutras, 1983). However, the authors did not describe the structure of the two filtration zones. The first zone, within the manure mat could have been caused by the disintegration of the manure aggregates and sedimentation of the manure colloids. However, it is less certain how the filtration zone at the boundary between the manure and soil surface was created, and therefore if it was a function of the manure composition, soil characteristics, or both.

4.2. Straining and filtration within the vadose zone

Micro-organisms in liquid manure are already in a dilute solution when the manure is applied to the soil. Those in solid manure are more associated with material surfaces and have to be dislodged by the impact of precipitation or the flow of water. Once in suspension, micro-organisms can be removed from the water stream by sieving within the manure material, filtration in smaller soil pores or pore necks, discontinuities in the macroporosity, or electrochemical retention on the surfaces of the soil particles. Sieving and filtration occurs due to the larger size of bacteria relative to pore diameters. In contrast to sieving and filtration, retention at the surface of soil particles depends on the interaction between the charged surface properties of both bacteria and soil particles, and both can be altered by the composition of the suspending liquid.

4.3. Charge mediated bacterial retention

Most soil mineral and organic surfaces have a net negative surface charge. The intrinsic charges at the soil particle surfaces are a function of the chemical composition of the soil minerals and the presence of organic material. Clay minerals carry a net negative charge due to the substitution of divalent cations in their alumino-silicate structure, and thus cationic exchange is the most important mechanism for the adsorption of organic compounds onto clays to form clay–organic complexes. Organic cations, such as protonated amines or quaternary ammonium cations, replace the inorganic cations on the clays. Such organic molecules have both hydrophobic and polar groups and can act as cationic surfactants conferring hydrophobic properties to the negatively charged clay surfaces.

Changes in the environmental pH can change the ionisation of surface groups and therefore change the
electrical potential at the surface. If the ionic strength of the solution is great then changes in pH will have a negligible effect (Jones, 1975). Increases in the electrolyte concentration result in the neutralisation of a greater number of charged surface loci by counter ions in the solution (Bennett and Hulbert, 1986). This leads to smaller electrostatic repulsion forces as the electrical double layer thickness is reduced (Jones, 1975). Presence of polyvalent ions (2–3–4) also favours aggregation (Jones, 1975; Hunter, 1981) although Wasserman and Felmy (1998), noted that this is true only at dilute concentrations of the suspending solution. As the ionic strength increases above 0.01 M the type of ions present in the solution has little effect on cell surface charge density. Hence, at large electrolyte concentration, and high thermal energy, the two surfaces can be brought sufficiently close for the short range London–van der Waals forces to take effect. Adsorption at this level occurs at what it is known as the primary minimum for the sum of attraction and repulsion forces. Although individually these attraction forces are weak, multiplicity of the connection points on the two charged surfaces can lead to an overall strong bonding. However, presence of the larger hydrated ions generally limits this occurrence in natural soil environments (Huang, 1995).

4.3.1. Surface charge properties of soil particles

The mineral phase of soils becomes strongly hydrated in the presence of water. Hydrophobic particles cannot compete with water and they become desorbed from the mineral surfaces and therefore interact mainly with soil organic matter (Boyd et al., 1991). Adsorption initiated by cationic exchange can be subsequently enhanced by hydrogen bonding, van der Waals, and hydrophobic bonding (Hayes and Himes, 1986). Water content and the pH of the system can also affect adsorption of organic acids onto mineral surfaces. A low pH favours adsorption of humic acids into clay interlayers. The resultant clay–organic complexes can have a strong affinity for suspended organic matter that is negatively charged, but still has hydrophobic properties (Mottlands, 1986; Schnitzer, 1986). For these reasons, the retentive capacity of the soils for hydrophobic compounds is directly correlated with the organic matter content. While most of the work on the retention of organic compounds on mineral surfaces has been conducted on crystalline clay minerals, the presence of iron oxides also has a significant impact on the retention of organic molecules in certain soil environments. Colloidal iron oxides have very active surfaces and often coat crystalline minerals, such as silica oxides, in the soil environment. Consequently, surfaces coated with oxide colloids are very active and interact readily with organic colloids (Huang, 1995). Soils, such as sandy soils, with a significant presence of iron oxide coatings have a large retention capacity for suspended organic compounds, despite their small organic matter content.

4.3.2. Surface charge properties of bacterial cells

The charge properties of bacterial surfaces depend on the constituents of their cell wall and the presence or absence of surface appendages. There are two basic organisational schemes for the bacterial cell wall, which correspond with the Gram staining reaction. Phospholipids are the chief lipids in many bacterial cell membranes (Van Bruggen, 1971). Phospholipids have a hydrophobic end, usually located within the cell membrane and a negatively charged terminal that can be located towards the surface of the cell wall. The cell wall also contains structural, metabolic and transport proteins as well as other components. The presence of free amine radicals on the proteins results in net positive charges. Lipids and proteins interact through polar and hydrophobic forces leading to the formation of lipoproteins in the cell wall. The relatively small amount of protein and the greater amount of phospholipids results in the bacterial wall mainly expressing hydrophobic and negative charges. Consequently, bacteria generally possess a net negative surface charge at most pH values found in soils (Stotzky, 1985). At first sight, this should suggest a repellent effect between bacteria and soil surfaces. However, because of the charge difference between these surfaces a potential exists between them and the bulk aqueous phase. To counterbalance the surface charge, ions of opposite charge are loosely attracted to the surface to form a diffuse double layer of ions. Thus, the charge density of a cell surface is a function of the intrinsic charge density within the cell wall and the induced charge density as a function of the ionic make-up of the solution. However, the net
charge of the cell surface and its associated double layer will be zero.

If the negatively charged cells come in contact with a positively charged surface the attachment tends toward 100% and few bacteria remain in the solution phase. As the concentration of the suspending solution increases, the percentage of cells that are attached to soil surfaces can decrease due to competition between anion groups on the cell surface and anions in solution (Makin and Beveridge, 1996). On the other hand, interactions that occur at the interface between cell surfaces and other surfaces present in soil (Marshall, 1985), can be influenced by the hydrophobic interactions between these surfaces and water. Whenever a charged surface is introduced in suspension, the bipolar water molecules reorient as a function of the surface charge signs and form an ordered layer on the surface. If two charged surfaces are suspended in water, they can attach to each other only by displacing this structured layer of water. This can only happen if the attraction forces overcome the water attachment forces.

Attachment of a cell to a surface can be influenced by the roughness of the cell surface (Dickson and Siragusa, 1994), or the presence of fimbriae (Stenström and Kjelleberg, 1985; Stenström, 1989) both of which can override the effect of surface charge or hydrophobicity. The presence of localised positively charged groups at the tip of hydrophobic fimbriae can be more essential in the adhesion process than the cell surface with an overall negative charge (Stenström, 1989). On the other hand, motile bacteria that possess fimbriae have increased detachment rates, positively correlated with the soil temperature, enhancing the potential for transport through soil (McCaulou et al., 1995). It is worth noting that under laboratory conditions, the addition of sub-neutral amounts of antibiotics, as used to increase feed efficiency in animals (Haas, 1985), can cause dramatic changes in the cell surface properties, and can even result in the obliteration of surface structures and appendages (Loubeire et al., 1993).

Presence of lipopolysaccharides polymer (mucilage), produced by active bacterial cells under specific conditions (e.g. starvation), may enhance their adhesion to mineral surfaces provided that the bacteria are brought in contact through other mechanisms and the contact period is long enough (Stotzky, 1985). On the other hand, initial attachment is impeded by the presence of lipopolysaccharides capsules if both the polymer and the surface are hydrated (Wrangstadh et al., 1986). Whereas, the adsorption of bacterial cells to soil particles that results from surface electrical charges is reversible under the range of concentrations found in soil solution, the attachment due to polysaccharide mucilage tends to be irreversible (Stotzky, 1985).

### 4.3.3. Impact of manure on charge mediated retention

Charged groups on soil and bacteria can act as donors or acceptors in the hydrogen bonding processes and therefore are strongly affected by pH changes (Bengtsson et al., 1993), and by the ionic strength of the solution. Adding electrolyte, such as manure liquids, to the suspending solution causes a compression of the diffuse parts of the electrical double layer and, in addition, ions are adsorbed in the Stern layer of both microbial cells and soil particle surfaces. This allows bacteria to approach soil surfaces at closer range. If the double layer is compressed sufficiently the range of the repulsive interaction of the double layer is reduced enough for the van der Waals forces to predominate. This is when flocculation at the surface of the soil particles may occur.

The pH of manure solution ranges between 8.0 and 8.5 (Table 2). Hence, the application of manure on neutral to slightly acidic soils could increase the pH temporarily. An alkaline pH can result in immobilisation of certain surface associated cations, thereby increasing the chances for bacteria to be removed from the adsorption sites and released into the soil solution (Stotzky, 1985). In contrast, volatilisation of ammonia from the liquid phase of manure can lead to temporary slight acidification of soils when excess H⁺ ions (left from NH₄⁺) remain in the solution. This is most likely to occur when manure is applied to warm, dry, alkaline soils. If the ionic strength of the solution is relatively high, then changes in pH will have a negligible effect (Jones, 1975; Jewett et al., 1995).

The EC of soil solution is generally around 0.3–1.2 mS cm⁻¹ (0.003–0.02 M), but is greater for saline soils. The ionic strength of manure and that of manure–water mixtures (Table 2) are significantly greater than these values. It seems reasonable to assume that the types of ions in the soil solution are less relevant in the bacteria–solid surfaces interaction, when manure liquids enter the soil.
4.4. Hydrophobic mediated bacterial retention

Hydrophobic interactions are identified by numerous studies in microbial cell surface phenomena (Doyle and Rosenberg, 1990). The effect of cell hydrophobicity on adhesion can be described as being less a function of the cell surface interaction and more of a function of the bacterial cell expulsion from the bulk of water due to the strong tension at the cell–water interface (water surface tension). Therefore, strong hydrophobicity of bacterial cell surface can result in large rates of bacterial adsorption at the solid–liquid interface (Lindqvist and Bengtsson, 1995). Hydrophobicity was positively correlated with bacteria adhesion to non-aqueous phases including mineral particles (Marshall, 1980, 1985; McAneney et al., 1982; Kjelleberg, 1985; Stenström, 1989), while hydrophilic strains are more likely to be found in the bulk water. Hence, hydrophobic bacteria will tend to attach themselves to the liquid–solid interface at greater rates than would hydrophilic bacteria. However, attachment is reversible, with a time scale for detachment being on the order of days or weeks. Slower attachment and detachment rates were observed for hydrophilic compared with hydrophobic strains, suggesting that the former would move further before being removed by attachment to soil, but once attached, they would become detached again at a slower rate (McCaulou et al., 1994). Consequently, hydrophobic strains have been found to move slower than hydrophilic ones (Huysman and Verstraete, 1993).

Surface roughness and presence of fimbriae as well as increased cell surface hydrophobicity favour cell adhesion to an air–water interface (Dahlbäck et al., 1981; Hermansson et al., 1982). Under field saturated conditions there are no air–water interfaces in the soil, barring the presence of trapped pockets of air. It might be assumed that presence of the charges on cell surfaces increase the chances of polar interactions with water molecules and therefore decrease the overall hydrophobicity. However, there is not always a direct link between surface charge and hydrophobicity, and a cell with small or no net surface charge can still be covered by a large number of positively and negatively charged sites. Presence of hydrophilic molecular groups on the cell surface can neutralise the effect of nearby hydrophobic molecular groups (Doyle and Rosenberg, 1990). Some relatively hydrophobic cells also have high negative electrokinetic potentials (van Loosdrecht et al., 1987). This combination may sound contradictory but the charged groups only occupy a minor fraction of the total surface area (under 10% of the surface), and the surface potential results only in part from charged groups on the outer surface, the rest originate from groups situated in deeper layers of the cell walls.

While most bacterial cells, both Gram-negative and Gram-positive, have a net negative charge, their hydrophobic character can vary within the same species or even strain (Stenström, 1989). Strongly hydrophobic cells can become irreversibly attached at the primary minimum of the electrical double layer. However, for more hydrophilic (charged) cells the electrokinetic potential becomes more important and bacteria can attach at the secondary minimum of the electrical double layer (van Loosdrecht et al., 1987). Lindqvist and Bengtsson (1991) showed that the surface charge generally plays a minor role in the association of bacterial cells with mineral surfaces compared to the hydrophobic characteristics, even in hydrophilic strains. However, surface charges may enhance the effect of hydrophobicity on adsorption especially at high electrolyte concentrations when the electric double layer is compressed. Consequently, it can be concluded that the surface charge as estimated by electrophoretic mobility (zeta potential) may be an indicator of the degree of sorption for hydrophilic bacteria, but has little relevance for hydrophobic strains (van Loosdrecht et al., 1987).

In practice, it can be expected that a combination of high hydrophobicity with low surface potential can be detrimental to bacteria survival, as such bacteria cannot move once the substrate is depleted. Other experimental evidence suggests that bacterial dispersal is a dynamic non-equilibrium process, possibly shaped by two sub-populations, one strongly (maybe irreversible) adsorbed to solid surfaces and one with very slow adsorption kinetics (Lindqvist and Bengtsson, 1991).

4.4.1. Impact of manure on hydrophobic mediated bacterial retention

The relative amounts of different lipopolysaccharides present on the surface of cells are under environmental control (Makin and Beveridge, 1996).
This indicates that the cell surface hydrophobicity is influenced by the growth medium. Cell surface hydrophobicity was found to be about eight times greater in groundwater compared to eutrophic lake water (Lindqvist and Bengtsson, 1991). The presence of a rich growth substrate, such as manure, may lead to reduction of cell hydrophobicity; therefore, increasing the effect of the surface charges on adsorption in the soil (Stotzky, 1985). Under the high ionic strength of manure solution, this can potentially lead to cell adsorption and cell aggregation. Increased sorption, rather than dispersal of bacterial cells, is associated with poor growth conditions, confirming that cultivation of bacteria on oligotrophic substrates results in increased cell hydrophobicity (Lindqvist and Bengtsson, 1991).

Adding charged salts and soluble organic compounds to water lowers its surface tension. For example, surface tension of human urine is around 42–63 mJ m$^{-2}$, compared to 72.8 mJ m$^{-2}$ for pure water (Reid et al., 1991). This should reduce the hydrophobic forces and the potential for retention of hydrophobic particles at phase interfaces. Lindqvist and Bengtsson (1995) found that the importance of hydrophobicity on the bacterial cell adsorption at surfaces within an aquifer was found to be greater when the groundwater solution had a small C content. Similar qualitative results were obtained by using ionised and uncharged bacterial sized microspheres, although quantitatively the results differed. Differences in the level of net surface charge and hydrophobicity of the microspheres compared to bacterial cells, and also to potential increased bacterial motility, could have been responsible for the contrast in quantitative rather than qualitative results.

4.5. Other cell characteristics affecting transport through the vadose zone

Gannon et al. (1991b) observed that bacterial transport through saturated sterilised soil was a function of cell size, with other surface characteristics having no significant impact. There was no information given on the amount of soluble organic carbon in the soil as a result of the sterilisation procedure. Similar conclusions were drawn after testing the transport of carboxylated artificial microspheres through repacked sandy soil columns (Harvey et al., 1991, 1995). Size selective transport is consistent with macropore flow being important in bacterial transport (Gannon et al., 1991a) in both undisturbed and disturbed soils. The presence of active macropores is nevertheless a function of the soil structure in undisturbed soils and grain size in disturbed soils.

The shape of the particles may influence the behaviour and structure of the electrical double layer. Jones (1975), and Hunter (1981), provided analyses of the impact of the double layer on the interaction between surfaces of spherical and cylindrical particles. Generally, however, the local radius of curvature of bacteria cells is large compared to the double layer thickness. Thus, it may be assumed that the actual shape of the bacterial cell has little influence on the double layer behaviour, and thus the model for plane surfaces can be used (Jones, 1975; Wasserman and Felmy, 1998).

4.6. Impact of organic carbon compounds on the retention of bacterial cells in the vadose zone

In natural soil environments there are soluble and insoluble C compounds that interact with mineral and particulate surfaces. Faster organic matter mineralisation can result in more water-soluble carbon in sandy soils compared with finer textured soils (Bernal et al., 1992). The strongly adsorbed organic material on the clay particles favours retention of non-ionic organic compounds. Dissolved humic substances have been found to associate predominantly by hydrophobic forces, as the apolar components of humic substances largely control their aggregation and reactivity in the environment (Piccolo et al., 1999). Dissolved soil organic acids act similarly to a cationic surfactant (Smith et al., 1991). Long carbon chain organic cationic surfactants displace the ionic cations bound at the soil surfaces. Cationic surfactant molecules attach themselves or as hemi-micelles to the cationic exchange sites in soil (Yeskie and Harwell, 1988). Thus, adsorption of cationic surfactants tends to increase the hydrophobic character of the soils and hence favour retention of suspended hydrophobic molecules (Mortlandt, 1986; Lee et al., 1989; Smith et al., 1991).

Retention of organic cations in soils is dependent on the soil cation exchange capacity (CEC). Hence, the use of cationic surfactants for increasing hydrophobic retention is expected to be more effective
in soils with greater clay content and hence greater cation exchange capacity (Mortlandt, 1986; Burris and Antworth, 1992). Most of the tests using organic cationic surfactants have been performed on aquifer materials with low organic matter content (Brown and Burris, 1996).

4.6.1. Impact of manure carbon compounds on the retention of bacterial cells

Increased amounts of organic matter in the unsaturated soil profile, as well as the greater organic and bacterial concentration following manure application, can enhance the number of possible interactions between a surfactant and the supplementary polar and non-polar surfaces present, hence increasing the complexity of the system. Dissolved soil organic matter tends to interact with the free ions and hydrophobic pollutants increasing their solubility, and hence favouring their transport (Smith et al., 1991). As the solubility of the hydrophobic molecules is increased by the presence of organic material in solution, manure application would be expected to favour more hydrophobic bacteria to stay in solution. Thus, the colloids left in solution are then less likely to become attached given their similar surface charge and hence favours transport (Smith et al., 1991). As the carbon compounds present in soil can interact with the soil surfaces in the same way as bacterial cells, the presence of a large amount of manure carbon compounds may increase the competition for the attachment sites in the soil (Stotzky, 1985).

Bacterial cells have very active surfaces where organic molecules from the solution can attach (Bengtsson et al., 1993). Polar or apolar organic molecules can interact with both the charged and the hydrophobic sites on bacterial cells similar to the interaction of the cells and organic material with soil surfaces. This leads to the flocculation of carbon compounds on the bacteria surfaces. Hence, the properties of the new particle, with bacteria at the centre, may have electrochemical properties that are entirely different from the electrochemical characteristics of the cell. The bacteria may metabolise some of the carbon compounds with the result that the electrochemical characteristics of the surfaces of bacteria-carbon compound complexes become fluid having the potential to vary independently from external factors. The attachment behaviour of those bacteria capable of degrading dissolved organic carbon is not very well understood. Cell flocculation in the presence of large amounts of dissolved organic carbon could be under some genetic control (Bossier and Verstraete, 1996).

While the electrochemical behaviour of the soil organic components has been extensively researched, the same cannot be said for the manure organic components applied to soil. However, manure organic matter was found to have similarities with the soil organic matter compounds (Businelli et al., 1999, Giusquiani et al., 1998).

Manure can be a significant source for colloidal matter of faecal origin. Greater concentrations of colloids favour their transport. Some of the colloids are attached to the soil particles in a single layer. Thus, the colloids left in solution are then less likely to become attached given their similar surface charge with the attached colloids (Kretzschmar et al., 1995). Alternatively, attachment of natural organic matter on the surface of colloids enhances colloid mobility by decreasing the attachment efficiency of the colloids to the matrix surface. Greater colloid stability due to adsorbed natural organic matter decreases soil retention capacity thereby increasing transport (Kretzschmar et al., 1995). At low colloid concentrations, soil retention capacity is maintained longer (Sata and Karathanasis, 1997). Given the large concentration of colloidal material in the manure solution, one cannot exclude the possibility that bacteria attach to smaller colloidal particles from the manure solution. This may retard adsorption to larger mineral particles and therefore enhance transport.

5. Conclusions

Survival and transport of manure bacteria in the vadose zone have been reviewed in terms of the impact that manure components may have on the physical and chemical properties of soil and on the surface characteristics of the bacteria themselves. The impact of manure components on the contaminant potential of manure bacteria can be manifold (Table 3). Manure changes the soil pH and increases the amount of salts and soluble and insoluble organic compounds. Bacteria grown in manure can exhibit surface properties entirely different from the strains grown in the laboratory. The presence of faecal and bedding particles at the soil surface has an impact on the likelihood that water from precipitation will enter the soil. The
Table 3: Potential impact of manure properties on the estimated contaminant risk to surface and groundwater resources

<table>
<thead>
<tr>
<th>Manure properties</th>
<th>Potential impact</th>
<th>Estimated contaminant risk to water resources</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Microbial population</strong></td>
<td>Source for contamination</td>
<td>Variable</td>
</tr>
<tr>
<td><strong>Dry matter content</strong></td>
<td>Filtration and straining of bacteria within manure and at manure soil interfaces</td>
<td>Diminishes</td>
</tr>
<tr>
<td></td>
<td>Protection from UV rays</td>
<td>Increases</td>
</tr>
<tr>
<td></td>
<td>Reduced hydraulic gradient at surface (vs. liquid manures) limits soil dispersion caused by the kinetic energy of rain; more pore available for transport</td>
<td>Increases infiltration risk</td>
</tr>
<tr>
<td></td>
<td>Decreased infiltration due to surface sealing</td>
<td>Increases runoff risk</td>
</tr>
<tr>
<td></td>
<td>Residual absorbent capacity of bedding material</td>
<td>Diminishes</td>
</tr>
<tr>
<td></td>
<td>At low dry matter content (liquid manure) flowing manure solution; flow rate and path dependent on hydraulic gradient at soil surface</td>
<td>Variable</td>
</tr>
<tr>
<td><strong>Ionic concentration and ionic species</strong></td>
<td>Favours interaction of like charged surfaces (soil and bacterial cells); increases cell retention</td>
<td>Diminishes</td>
</tr>
<tr>
<td></td>
<td>Competition for retention sites; decreases cell retention</td>
<td>Increases</td>
</tr>
<tr>
<td></td>
<td>Increased soil structural stability; improved macropore stability and continuity</td>
<td>Increases</td>
</tr>
<tr>
<td></td>
<td>If high Na⁺ content; clay dispersion; decrease aggregate stability and thus macropore integrity</td>
<td>Diminishes, Variable</td>
</tr>
<tr>
<td></td>
<td>Available mineral nutrients from manure can modify the physiological response of soil organisms</td>
<td>Variable</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td>Initial manure pH is slightly alkaline; ammonia volatilisation can acidify slightly the soil environment</td>
<td>Variable (likely not significant)</td>
</tr>
<tr>
<td><strong>Soluble and colloidal, charged and hydrophobic carbon compounds</strong></td>
<td>Interaction with bacterial cell charged and hydrophobic surface loci</td>
<td>Variable</td>
</tr>
<tr>
<td></td>
<td>Surfactant-like behaviour may favour flocculation and retention</td>
<td>Diminishes</td>
</tr>
<tr>
<td><strong>Available carbon</strong></td>
<td>Increases the physiological response of soils. Accelerates soil metabolic activities, increasing predation and competitive pressures</td>
<td>Diminishes, Variable</td>
</tr>
<tr>
<td><strong>High ammonia and fatty acids concentration</strong></td>
<td>Tonic effects within manure</td>
<td>Diminishes</td>
</tr>
<tr>
<td></td>
<td>Tonic effect in soil after application can modify the interaction between manure and soil microbes</td>
<td>Variable</td>
</tr>
</tbody>
</table>

Available carbon and nutrients in manure can affect the survival of manure pathogens in soil in part because the same components can also impact the soil microbial population thereby influencing the interaction between the two groups of micro-organisms. Manure impacts on all aspects of transport and survival of manure pathogens in the soil environment need to be fully quantified before an evaluation of the importance of each type of impact and their interactions can be appropriately done.

Consideration needs to be given to the impact of manure characteristics on the transport of both precipitation (rainfall and irrigation water) and bacteria, shortly after manure application, as well as over longer periods of time. Thus, future research is required to evaluate the effect of manure composition on soil properties controlling water transport, the flow regime within the soil, and the potential impact of manure components on the water partitioning at the soil surface. There is a need to bridge the gap between the practical information on the contaminant potential of manure and the detailed assessments that are relevant to the interaction of bacterial cells with soil surfaces. More understanding is required on how soluble and colloidal organics in manure interact with the surfaces of bacteria and affect their retention to soil surfaces. Given
that many of the studies on surface properties have been performed in laboratories, there is a need to evaluate the level at which surface properties derived from such studies can be used to estimate bacterial retention and transport in field soils.

References


