Environmental Management (2007) 40:958–965
DOI 10.1007/s00267-007-9012-3

Efficacy of Vegetated Buffers in Preventing Transport of Fecal Coliform Bacteria from Pasturelands

Timothy J. Sullivan · James A. Moore · David R. Thomas · Eric Mallery · Kai U. Snyder · Mark Wustenberg · Judith Wustenberg · Sam D. Mackey · Deian L. Moore

Received: 28 December 2006 / Accepted: 17 June 2007 / Published online: 5 September 2007

Abstract An experimental study was conducted in Tillamook, Oregon, USA, to quantify the effectiveness of edge-of-field vegetated buffers for reducing transport of fecal coliform bacteria (FCB) from agricultural fields amended with dairy cow manure. Installation of vegetated buffers on loamy soils dramatically reduced the bacterial contamination of runoff water from manure-treated pasturelands, but the size of the vegetated buffer was not an important determinant of bacterial removal efficiency. Only 10% of the runoff samples collected from treatment cells having vegetated buffers exhibited FCB concentrations >200 colony forming units (cfu)/100 mL (a common water quality standard value), and the median concentration for all cells containing vegetated buffers was only 6 cfu/100 mL. The presence of a vegetated buffer of any size, from 1 to 25 m, generally reduced the median FCB concentration in runoff by more than 99%. Results for FCB load calculations were similar. Our results suggest that where substantial FCB contamination of runoff occurs from manure-treated pasturelands, it might be disproportionately associated with specific field or management conditions, such as the presence of soils that exhibit low water infiltration and generate larger volumes of runoff or the absence of a vegetated buffer. Buffer size regulations that do not consider such differences might not be efficient or effective in reducing bacterial contamination of runoff.

T. J. Sullivan (✉) · K. U. Snyder · S. D. Mackey · D. L. Moore
E&S Environmental Chemistry, Inc., P.O. Box 609, Corvallis, OR 97339, USA
e-mail: tim.sullivan@esenvironmental.com

J. A. Moore · D. R. Thomas
Oregon State University, Corvallis, OR 97331, USA

E. Mallery
Oregon Streamside Services, Tillamook, OR 97141, USA

M. Wustenberg · J. Wustenberg
Kilchis Dairy Herd Services, Bay City, OR 97141, USA

Keywords Fecal coliform bacteria · Vegetated buffer strip · Best management practice · Runoff · Manure

Agricultural activities associated with livestock management can impact the quality of pasture runoff and adjacent surface waters. Field spreading of livestock manure can contaminate streams and estuaries with fecal coliform bacteria (FCB), signaling the possible presence of fecal-associated pathogens and impairing beneficial uses. The installation of vegetated buffers between manure application areas and surface waters is a common best management practice (BMP; US EPA 2003). It is of critical importance to both farm economics and water quality that we determine edge-of-field buffer widths that will simultaneously protect water quality and require the smallest buffer width necessary.

Numerous studies have evaluated the influence of agricultural practices on microbiological quality of runoff water (Castelle and others 1994; Fajardo and others 2001; Johnson and others 2003; Stoddard and others 1998; Wenger 1999). Quantification of impacts is difficult because the extent of bacterial pollution is related to climatological factors such as rainfall amount and intensity, as well as microbial populations and die-off. Bacteria transport varies with initial population, soil conditions, temperature, sunlight, and organic matter (Gerba and others 1975). For these, and perhaps other, reasons, empirical data correlating manure application with quality of runoff water frequently exhibit contradictions (Edwards and others 1997).

Fecal coliform bacteria concentration is a common indicator of bacterial contamination, implying the potential presence of microorganisms that are pathogenic to humans (Entry and others 2000). Homeothermic animals shed large amounts of these bacteria in their feces, and their presence in water suggests fecal pollution. The US Environmental Protection Agency required that FCB concentrations not exceed 200 colony forming units (cfu)/100 mL for contact recreation and 14 cfu/100 mL for shellfish harvesting (US EPA 1976). Most pathogenic bacteria are removed by physical and chemical adsorption within the soil profile (Gerba and others 1975), and FCB concentrations therefore typically decline substantially when transported through soil, suggesting that transport to surface water occurs mainly by surface flow (Abu-Ashour and others 1994; Howell and others 1996; Huysman and Verstraete 1993; Kunkle 1970).

Buffers are strips of land that are managed so that pollutant transport does not occur from pollution source areas to commodities that we wish to protect, including surface water. Pollution control is achieved through natural processes that promote leaching and prevent or retard overland transport. Although these functions are well established, the degree to which they can be enhanced by the installation of larger buffers has not been quantified (Castelle and others 1992, 1994; Dosskey 2000; Roodsari and others 2005).

The objectives of the research reported here were to measure edge-of-field transport of FCB during rainstorms from pasture lands amended with dairy cow manure and to determine the effectiveness of vegetated buffers of varying sizes for reducing bacterial transport.

Methods

We conducted a series of experiments over a 2-year period in Tillamook, Oregon, USA, to quantify the FCB removal efficiencies of edge-of-field vegetated buffers during nine rainstorms. The experimental system consisted of 17 treatment cells, each about 14 m across and 30 m from top to bottom. Cells exhibited different buffer widths (0, 1, 3, 8, 15, and 25 m) and slopes (3.8% and 7%). A runoff water collection system was installed, with which one could consecutively collect, at the base of each treatment cell, samples from 10 locations. Each cell (Figure 1) consisted of a simulated pasture area, which was periodically mowed; an undisturbed simulated buffer, planted with typical native plants; and a simulated stream (ditch line). Each cell was hydrologically isolated by ditching and berm installation. Soils in the project area are Quillayute silt loams (Bowlsby and Swanson 1964) having average silt particle size (2–50 μm) of 50% (moderate slope class) to 56% (gentle slope class) and clay particle size (<2 μm) of 10% (gentle slope class) to 17% (moderate slope class). Three of the experimental buffer cells were replicated for width, and there were two control cells that received no manure treatment.

All treatment plots were constructed to allow runoff collection to be spatially and temporally replicated. Gutter systems, separated into compartments, each connected below to a runoff collection tube and sample bottle, collected composite samples of overland flow and shallow groundwater (≤15 cm) flow that drained from the treatment cell and associated buffer during rainstorms

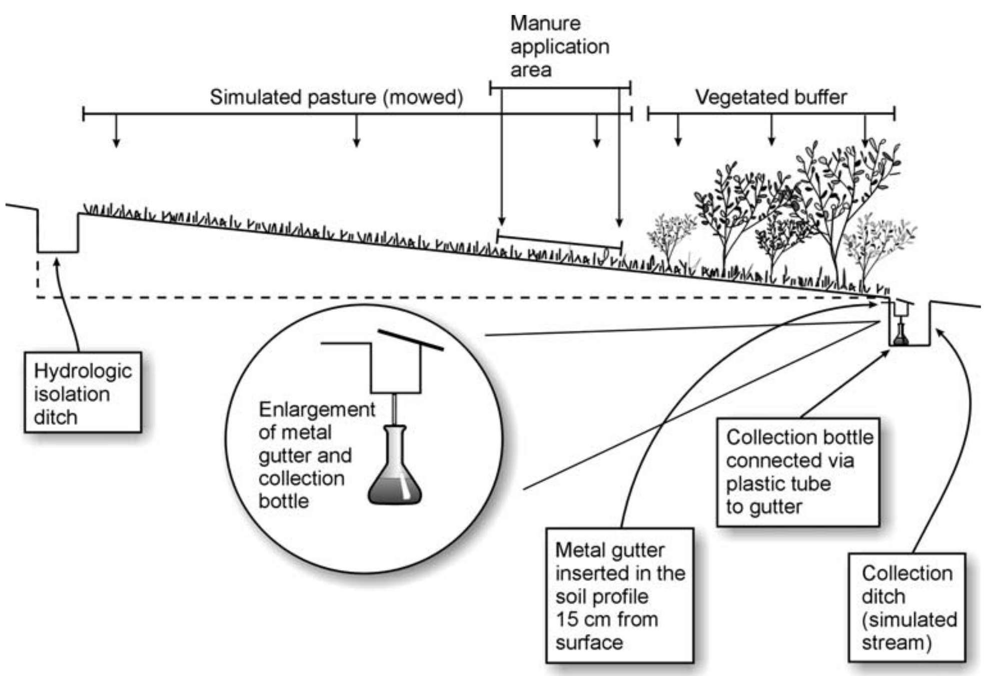

Fig. 1 Schematic drawing (not to scale) of cross-sectional side view of one treatment cell. Each cell was 30 m long and about 14 m wide. Manure was applied on an 11-m strip immediately above the buffer. The width of the buffer area was variable

(Figure 1). Runoff collection occurred within the middle third of each buffer width, thereby avoiding collection of runoff near either of the sides, which could be affected by lateral flow toward or away from the cell.

Manure was obtained as fresh scrapings from the nearby dairy barn and applied (132 L) in advance of each rainstorm across an 11-m width of each treatment cell above the interface between pasture and buffer. The manure loading rate uphill from the simulated stream was 12.3 L/m, applied at a spreading density of 1.3 L/m^2, which would approximate agronomic rates.

Rainstorms began within 1 to several days after manure application. We then quantified the following: precipitation input; infiltration rate; discharge to simulated stream via combined overland flow and shallow (~15 cm) groundwater flow; bacterial concentrations (cfu/100 mL) in runoff; bacterial flux (e.g., cfu/storm/m); and bacterial removal efficiency (percent removed, normalized to zero buffer treatment) under differing hydrological conditions. Note that the bacterial removal efficiency of a given buffered cell as a function of the bacteria flux with no buffer is a good reflection of buffer functionality. Our aim was to quantify improvement attributable to a given buffer size in comparison with the absence of any vegetated buffer, rather than to quantify what percent of the FCB applied in the manure spreading was leached from the site.

Bacteria samples were collected, generally at ~24-h intervals, during rainstorms and aliquots of pooled samples were transferred to sterilized 125-mL bottles and transported to the analytical laboratory for processing. FCB were determined using the membrane filter technique (APHA 1992). About 10% of the samples analyzed were allocated to quality assurance/quality control (QA/QC), and these included field duplicates of pooled samples and blanks to quantify sampling and analytical variability. Relative error (RE), expressed as

$$\mathrm{RE} = \frac{|\mathrm{C}_1 - \mathrm{C}_2|}{(\mathrm{C}_1 + \mathrm{C}_2)/2} \chi 100$$

(where C_1 and C_2 are the FCB concentrations of the duplicate samples) and absolute error (difference between duplicate samples) were calculated for results of duplicate analysis (field splits) of FCB. For FCB duplicate pairs (n = 39), the median absolute error was 80 cfu/100 mL. Median relative error (MRE) was 46.5%. A total of 38.5% of the duplicate pairs had a RE of 75% or greater. For the duplicate sample pairs that had FCB (200 cfu/100 mL (16 pairs), the MRE was 21.6%, and a total of 15% of those had a RE of 75% or greater.

The first storm determined baseline levels of FCB (e.g., due to feces from pasture fauna). The subsequent eight storms were sampled following application on each cell (except controls) of fresh dairy cow manure. The bacteria flux during each storm was calculated for each cell by multiplying the average runoff volume for the cell slope class by the total measured bacteria concentration in the combined runoff collected from each cell. Data were evaluated for within-cell and between-cell differences in FCB concentration and bacterial removal efficiency, normalized by the measured flux from the treatment cells with no buffer (zero buffer cells).

The Proc Mixed procedure in SAS was applied to the transformed concentrations to obtain a P-value for comparing the narrow (1 and 3 m) and wide (8, 15, and 25 m) widths for each of the gentle and moderate slopes (SAS Institute, Inc. 1999). In the mixed linear models, the cells within width, storms, and the interaction components of storms with width and cells within width were all modeled as random effects. The default Satterthwaite approximation for SAS was used to obtain an approximate standard error and degrees of freedom for each t-test and corresponding P-value.

Regression curves were used to smooth scatter plots of mean concentrations of bacteria versus buffer width for the cells within each slope class by fitting models for the mean concentration (μ) on width (w) of the form

$$\mu = \alpha \exp(\beta w) \gamma$$

where γ is the lower asymptote corresponding to no application of bacteria, $\alpha + \gamma$ is the intercept corresponding to no buffer, and β is the slope parameter, with the slope of the regression curve satisfying

$$\frac{d\mu}{dw} = \beta(\mu - \gamma).$$

Thus, the slope of the regression curve is proportional to the distance of the mean from the lower asymptote. The Poisson distribution and parameter constraints, $\alpha \geq 0$ and $\beta \geq 0$, were specified such that resulting regression curves were nonincreasing as the buffer width increased.

Results

Bacteria measurements indicated an average FCB concentration of about 26 × 10^6 cfu/100 mL for the manure that was spread on the treatment cells. Thus, the bacteria loading on each of the treatment cells in advance of each storm was about 3.9 billion cfu upslope from each linear meter of simulated streambank.

Sampling occurred during several of the largest storms of the study period (Table 1); five included more than 7.5 cm of rain and the largest included 20.4 cm of rain. The 10-year return frequency for a 24-h storm in this area is

Table 1 Precipitation amounts received and fluxes during each of the storms sampled for runoff water quality

Storm	Precipitation (cm)	Precipitation flux to each experimental cell per unit pasture length (L/m)	Maximum precipitation intensity (cm)	
			1-h Period	4-h Period
1	13.4	1584	0.66	2.31
2	4.1	480	0.48	1.45
3	10.7	1269	0.94	2.57
4	4.5	537	0.89	1.30
5	3.3	387	0.18	0.46
6	9.6	1145	1.30	2.71
7	20.4	2407	0.63	2.66
8	6.7	788	0.74	2.63
9	8.1	954	0.37	1.00

Table 2 Amount and percent (calculated as a percentage of precipitation) of runoff, by site and storm

Storm	Storm runoff (L/m)[a]		Percent runoff (%)[b]	
	Gentle slope	Moderate slope	Gentle slope	Moderate slope
1	3.40	1.84	0.21	0.12
2	0.49	0.27	0.10	0.06
3	0.40	0.35	0.03	0.03
4	0.67	0.65	0.12	0.12
5	2.26	1.08	0.58	0.28
6	0.92	0.45	0.08	0.04
7	1.55	1.04	0.06	0.04
8	0.72	0.71	0.09	0.09
9	0.34	0.27	0.04	0.03
Ave.	1.19	0.74	0.15	0.09

[a] Liters of runoff water collected per meter of simulated stream

[b] Percent runoff calculated based on estimated runoff from treatment cells divided by estimated precipitation

about 12 cm and the 2-year return frequency is about 9 cm (Miller and others 1973). During about half of the sampled storms, the amount of rainfall received by each cell exceeded about 1000 L upslope of each meter of simulated stream. Infiltration was estimated as the difference between the estimated cell runoff and the total precipitation to the cell surface. On average, more than 99% of the rainfall infiltrated the loamy soils of the treatment site, without generating surface or shallow (<15 cm) runoff. Only 0.3–2.3 L of runoff water per meter of simulated pasture/stream interface (mean = 1 L) was collected from each experimental cell during the sampled storms that included manure application (Table 2). The maximum storm 1-h precipitation amounts ranged from 0.18 to 1.30 cm. More than half of the storms had maximum 4-h precipitation amounts of more than 2 cm (Table 1).

Concentrations of bacteria were often high in the runoff from the zero buffer cells. Over the course of the eight treatment storms, 90% of the samples from the zero buffer cell on the gentle slope had FCB concentration >200 cfu/100 mL; the median FCB concentration was 16,500 cfu/100 mL. Similarly, 67% of the samples from the zero buffer cell in the moderate slope class had FCB >200 cfu/100 mL, and the median FCB concentration was 620 cfu/100 mL (Table 3). In marked contrast, less than 26% of the samples collected from any of the various buffer sizes had FCB >200 cfu/100 mL (10% overall for all buffer sizes combined). The median FCB concentration for all cells containing buffers was 6 cfu/100 mL, and none of the buffered cells had median FCB concentration greater than 29 cfu/100 mL (Table 3).

Median volume-weighted average FCB concentrations in runoff from the zero buffer cells across storms 2 through 9 were 5896 cfu/100 mL (gentle slope) and 786 cfu/100 mL (moderate slope), respectively. Volume-weighted average FCB concentrations were much lower (≤34 cfu/100 mL) in all cells that contained vegetated buffers (Table 3). Results for the background storm (all cells sampled without prior manure amendment) and for all storms in the two control cells (no manure application during any of the storms) were generally similar to average results for the storms and cells that involved manure application to cells containing a vegetated buffer (Table 3).

For both slope classes, the smoothed function describing the relationship between mean FCB concentration and buffer size decreased to within 0.006 cfu/100 mL of the background value, indicating bacteria concentration without manure application, at a buffer size smaller than 2 m (Table 4). This suggests that runoff from a manure-treated cell having a buffer larger than about 2 m was roughly equivalent to runoff from a cell with no manure application.

Our estimates of runoff were combined with discharge-weighted average FCB concentrations to yield estimates of bacterial load per unit pasture length from each experimental cell during each storm (Table 5). There was considerable variation from storm to storm in the FCB load delivered from a given treatment cell. Loads from the zero buffer cells often exceeded 10,000 cfu/m during an individual storm in the gentle slope class (Table 5).

The presence of a vegetated buffer of any size, from 1 to 25 m, generally reduced the median FCB concentration of runoff by more than 99% (Table 3). The 75th percentile value was <1% for all cells except the 3-m buffer on the gentle slope site (2.5%) and the 3-m buffer on the moderate slope site (3.0%). There was only limited evidence that the smallest buffers (1 m and 3 m) might have been slightly

Table 3 Median and quartile values of the measured concentration of FCB and percent of runoff samples that exceeded FCB concentration of 200 cfu/100 mL

Sample type[a]	Buffer size (m)	n	Bacteria concentration (cfu/100 mL)			Percent of samples exceeding 200 cfu/100 mL	Median volume-weighted average bacteria concentration (cfu/100 mL)
			Percentile				
			25	50	75		
Gentle Slope Class							
Reference storm (Storm #1)	Variable	26	0	0	2	4	4
Control	8	18	0	9	25	6	6
Treatment	25	20	0	0	4	5	1
Treatment	15	20	0	2	15	20	0
Treatment	8[b]	42	0	0	28	12	10
Treatment	3[b]	38	1	29	198	26	34
Treatment	1	21	0	10	73	14	10
Treatment	0	21	3,100	16,500	95,000	90	5,896
Moderate Slope Class							
Reference storm (Storm #1)	Variable	19	0	6	10	0	6
Control	8	21	0	0	3	5	1
Treatment	25	20	0	3	28	10	6
Treatment	15	19	0	0	10	5	2
Treatment	8	20	0	0	0	0	0
Treatment	3[b]	41	0	7	25	7	16
Treatment	1	21	0	0	13	0	6
Treatment	0	21	150	620	1,900	67	786

[a] Reference storm (Storm #1) did not include manure treatment on any cells. Treatment cells include all cells that received manure application (all except control cells, during storms 2 through 9)

[b] Cells that contained the 3-m buffer on both gentle and moderate slopes and the 8-m buffer on the gentle slope class were replicated. Therefore, approximately twice as many samples were collected from these buffer types as compared with others

Table 4 Coefficients and *P*-values for regression equations describing the relationships between mean FCB concentration and buffer size

Coefficient	Gentle slope		Moderate slope	
	Estimate	*P*-Value	Estimate	P-Value
α	1879.498	<0.001	17.865	0.004
β	−6.184	<0.001	−7.310	0.968
γ	1.806	0.011	0.845	0.004

less efficient at removing FCB from runoff as compared with the larger buffers (8–25 m). For the gentle slope class, the one-sided *P*-value comparing mean values of small versus larger buffers with square root transformations was nearly significant ($P = 0.065$). For the moderate slope class, the *P*-value was 0.7.

Discussion

There was considerable variation from storm to storm in the FCB load delivered from a given treatment cell. Loads were very high from the zero buffer cells, often exceeding 10,000 cfu/m of pasture length (median: 50,082) during an individual storm in the gentle slope class. We found much lower values and considerable variability in the estimates of bacterial load from manure-treated cells of differing vegetated buffer sizes within a given storm (Table 5).

During some storms, the cells having larger vegetated buffers and/or the control cells (no manure application) exhibited higher FCB load than did the cells having shorter vegetated buffers (Table 5). It is important to note, however, that the FCB load was generally much higher in the zero buffer cells than in any of the buffered cells. There are many possible reasons for the observed variability in FCB load among cells containing varying buffer sizes. These include, for example, runoff discontinuity due to soil heterogeneity and differences in microtopography (cf. Fiedler and others 2002; Roodsari and others 2005), bacteria contributed by pasture fauna, the influence of flow through lateral macropores (e.g., associated with mole tunnels), and sampling or analytical error. However, there was no indication that the FCB flux varied consistently as a function of vegetated buffer size.

There was a general tendency of vegetated buffer cells on the gentle slope class to yield equal or higher FCB

Table 5 Calculated bacterial flux (load), in cfu/m of pasture length intercepted, for each experimental cell throughout the duration of each storm

Vegetated filter strip size[a]	Reference storm	Manure treatment storms									
	1	2	3	4	5	6	7	8	9	Ave.[b]	Median[b]
Gentle Slope Class											
0	0	484	2,106,720	14,676	70,704	1,653	10,322,607	781,062	29,459	1,665,928	50,082
1	197	0	13,845	75	293	5,074	120	63	1,068	2,567	207
3[c]	13	4	1,684	330	419	2,817[c]	83	110	1451	862	375
8[c]	217	0	1337	101	552	8,100	9	0	70	1,271	86
15	522	0	7,022	1,192	2,960	ND	6	0	0	1,597	6
25	11	0	0	0	174	2,932	295	0	20	428	97
Control	8,905	0	9,177	0	91	1,155	374	57	958	1,476	232
Moderate Slope Class											
0	164	1	5,584	4,561	5,348	14,276	750	6,182	24,313	7,627	5,466
1	134	0	45	0	98	0	53	51	83	41	48
3[c]	24	10	2,880	118	167	45	33	22	982	532	82
8	0	0	0	0	56	14	20	0	0	11	0
15	2,126	0	14,484	61	130	3	13	20	3	1,839	17
25	113	0	45,021	195	90	20	0	0	241	5,696	55
Control	0	0	35	0	101	2	0	7	9	19	5

[a] Vegetated filter strip sizes that were replicated (indicated with asterisk) are expressed as the average of the two replicates

[b] Average or median of all manure treatment storms (storms 2 through 9)

[c] Storm flux for the 3-m vegetated filter strip during storm 6 was calculated using data from only one of the two 3-m vegetated filter strip cells

concentrations in runoff as compared with comparable cells on the moderate slope class. One possible explanation for this result could be the observed differences in infiltration. Estimated runoff volumes were consistently lower for the moderate slope cells than for the gentle slope cells (Table 2).

On loamy soils of this study, infiltration of precipitation typically exceeded 99% (Table 2) and, therefore, the FCB flux in runoff from pasture to stream was low where there were vegetated buffers, even buffers as small as 1 m. In the absence of vegetated buffers, however, the flux of FCB from pasture to stream was higher, on average, by about two orders of magnitude. Such loads might impact FCB concentration in streamwater passing through manure-treated pastureland. In contrast, the FCB flux from cells that contained vegetated buffers was almost uniformly low (Table 5).

We compared FCB concentrations within each experimental cell with two variables that reflected precipitation amount and two variables that reflected precipitation intensity. The variables selected for analysis were as follows:

- Cumulative precipitation amount during the sampling interval
- Cumulative precipitation amount since manure spreading
- Maximum 1-h precipitation amount within the sampling interval
- Maximum 4-h precipitation amount within the sampling interval

In general, there was not a clear relationship between FCB concentration in pasture runoff and any of these precipitation variables. However, there was a tendency toward lower FCB concentration when precipitation amount or intensity was low. FCB concentrations were more variable when precipitation amount or intensity was higher. In the cells that contained small buffers (1 and 3 m), FCB concentrations in runoff generally exceeded 200 cfu/100 mL only when the 4-h precipitation intensity exceeded 0.5 cm or when the cumulative precipitation during the sampling interval exceeded 4 cm. In the case of no vegetated buffer, a 4-h precipitation intensity above 1 cm or a cumulative precipitation amount during the sampling interval above 4 cm was generally required to yield FCB concentration in runoff above 100,000 cfu/100 mL.

Our findings conflict with those of earlier studies (Coyne and others 1995, 1998; Young and others 1980), which concluded that 10-m vegetated buffers were not adequate in meeting FCB water quality standards. However, these earlier studies employed experimental designs based on high rates of artificial irrigation to force soil saturation and overland flow. During our study, natural rainfall was insufficient to produce overland flow, even though we sampled during large rain events (Table 1).

Results obtained by Roodsari and others (2005) agree with our findings. They used a rainfall simulator at 61 mm/h to quantify the effects of vegetated buffers on transport of FCB released from surface-applied bovine manure on 6-m experimental lysimeters with 20% slope. Runoff was 12% of simulated rainfall on clay loam plots, but only 2% of simulated rainfall on sandy loam plots. The amount of FCB recovered in runoff at the base of the lysimeters was 1% of the applied bacteria amount on the vegetated clay loam soil and nondetectable on the vegetated sandy loam soil. Both runoff and FCB fluxes were much higher on bare soil (nonvegetated) plots. Roodsari and others (2005) concluded that vegetated buffers can dramatically reduce transport of FCB, even on steep (20%) slopes, especially in soils having high infiltration, such as sandy loam. Both our results and those of Roodsari and others (2005) suggest that infiltration is the primary mechanism responsible for attenuation of FCB surface transport.

This research demonstrated the importance of vegetated buffers in reducing the contamination of runoff with FCB subsequent to manure spreading. Although small (1 and 3 m) buffers removed FCB from runoff as well, or nearly as well, as larger (8–25 m) buffers, there might be other environmental benefits (e.g., nutrient management, wildlife habitat, stream shading) associated with larger buffers. However, with respect to bacterial contamination of surface waters, new federal regulations that specify uniform minimum buffer sizes of 10.8 m (cf. US EPA 2003) may be unnecessary for water quality protection under some soil and slope conditions.

Acknowledgments This research is a contribution of the Tillamook Estuaries Partnership. We wish to thank J. Oldenkamp for allowing this research to be conducted on his farm. Assistance was provided by J. Charles, T. McDonnell, L. Sullivan, J. Sullivan, K. Foster, B. Lambert, B. Apple, T. Downing, C. Knutsen, W. Matthews, P. Measeles, S. Reiersgaard, D. Sowers, M. Trenholm, and E. Nigg. Funding was provided by the Oregon Department of Environmental Quality, US Environmental Protection Agency, Oregon State University Agricultural Research Foundation, and Tillamook County Creamery Association (TCCA). This article has not been officially reviewed by these organizations, however, and no endorsement is implied.

References

Abu-Ashour J, Joy DM, Lee H, Whitely HR, Zelin S (1994) Transport of microorganisms through soil. Water Air and Soil Pollution 75:141–157

APHA (American Public Health Association). (1992) Standard methods for the examination of water and wastewater, 18th ed. American Public Health Association, Washington, DC

Bowlsby CC, Swanson RC (1964) Soil survey, Tillamook Area, Oregon. US Department of Agriculture, Soil Conservation Service, Series 1957, No. 18. US Department of Agriculture, Washington, DC

Castelle AJ, Conolly C, Emers B, Metz ED, Meyer S, Witter M, Mauermann S, Erickson T, Cooke SS (1992) Wetland buffers: Use and effectiveness. Adolfson Association for Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia, WA

Castelle AJ, Johnson AW, Conolly C (1994) Wetland and stream buffer size requirements: A review. Journal of Environmental Quality 23:878–882

Coyne MS, Gilfillen RA, Rhodes RW, Blevins RL (1995) Soil and fecal coliform trapping by grass filter strips during simulated rain. Journal of Soil and Water Conservation 50(4):405–408

Coyne MS, Gilfillen RA, Villalba A, Zhang Z, Rhodes RW, Dunn L, Blevins RL (1998) Fecal bacterial trapping by grass filter strips during simulated rain. Journal of Soil and Water Conservation 53(2):140–145

Dosskey MG (2000) How much can USDA riparian buffers reduce agricultural nonpoint source pollution? In: Wigington PJ Jr, Beschta RL (eds), Riparian ecology and management in multi-land use watersheds. American Water Resources Association, Middleburg, VA, pp 427–427

Edwards DR, Coyne MS, Vendrell PF, Daniel TC, Moore PA, Jr., Murdoch JF. (1997) Fecal coliform and streptococcus concentrations in runoff from grazed pastures in northwest Arkansas. Journal of the American Water Resources Association 33(2):413–422

Entry JA, Hubbard RK, Thies JE, Fuhrmann JJ (2000) The influence of vegetation in riparian filterstrips on coliform bacteria: II. Survival in soils. Journal of Environmental Quality 29:1215–1224

Fajardo JJ, Bauder JW, Cash SD (2001) Managing nitrate and bacteria in runoff from livestock confinement areas with vegetated filter strips. Journal of Soil and Water Conservation 56(3):185–191

Fiedler FR, Frasier GW, Jorge A, Ramirez JA, Ahuja LR (2002) Hydrologic response of grasslands: Effects of grazing, interactive infiltration, and scale. Journal of Hydrologic Engineering 7(4):293–301

Gerba CP, Wallis C, Melnick JL (1975) Fate of wastewater bacteria and viruses in soil. Journal of Irrigation and Drainage Division, American Society of Civil Engineering IR 3:157–174

Howell JM, Coyne MS, Cornelius PL (1996) Effect of particle size and temperature on fecal bacterial mortality rates and the fecal coliform/fecal streptococci ratio. Journal of Environmental Quality 25:1216–1220

Huysman F., Verstraete W (1993) Water facilitated transport of bacteria in unsaturated soil columns: Influence of cell surface hydrophobicity and soil properties. Soil Biology & Biochemistry 25:83–90

Johnson JYM, Thomas JE, Graham TA, Townshend I, Byrne J, Selinger LB, Gannon VPJ (2003) Prevalence of *Escherichia coli* O157:H7 and *Salmonella* spp. in surface waters of southern Alberta and its relation to manure sources. Canadian Journal of Microbiology 49:326–335

Kunkle SH (1970) Sources and transport of bacterial indicators in rural streams. In: Interdisciplinary aspects of watershed management. American Society of Civil Engineers, Bozeman, MT, pp 105–123

Miller JF, Frederick RH, Tracey RJ. (1973) Precipitation frequency atlas of the western United States. NOAA Atlas 2. 11 vols. National Weather Service, Silver Spring, MD

Roodsari RM, Shelton DR, Shirmohammadi A, Pachepsky YA, Sadeghi AM, Starr JL. (2005) Fecal coliform transport as affected by surface condition. Transactions of the American Society of Agricultural Engineers 48(3):1055–1061

SAS Institute, Inc. (1999) The mixed procedure SAS/STAT users guide. SAS Institute, Inc., Cary, NC

Stoddard CS, Coyne MS, Grove JH. (1998) Fecal bacterial survival and infiltration through a shallow agricultural soil: timing and tillage effects. Journal of Environmental Quality 27:1516–1523

US EPA (US Environmental Protection Agency) (1976) Fecal coliform bacteria. In: Quality criteria for water. US Environmental Protection Agency, Washington, DC, pp 42–50

US EPA (US Environmental Protection Agency). (2003) National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitation Guidelines and Standards for Concentrated Animal Feeding Operations (CAFOs). Final Rule. Federal Register, February 12, (2003) Available from http://www.cfpub.epa.gov/npdes/afo/cafofinalrule.cfm

Wenger S (1999) A review of the scientific literature on riparian buffer width, extent, and vegetation. Institute of Ecology, University of Georgia, Athens, GA

Young RA, Huntrods T, Anderson W (1980) Effectiveness of vegetated strips in controlling pollution from feedlot runoff. Journal of Environmental Quality 9:483–487