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Reducing microbial contamination in storm runoff from high use areas on California coastal dairies

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ABSTRACT

High use areas are a fundamental part of California coastal dairies and grazing livestock ranches as feeding areas, nurseries, and sick pens. High stocking densities and daily use in these areas lead to soil surfaces devoid of vegetation and covered in manure, with high potential for manure transport during winter rains to receiving waters regulated for shellfish harvesting and recreation. We characterized the association between California's Mediterranean climate and a series of existing and proposed management practices on fecal coliform bacteria (FCB) transport from high use areas on dairies and ranches. Results from 351 storm runoff samples collected below 35 high-use areas indicate that removal of cattle during winter, locating high use areas on level ground, application of straw and seeding, and vegetative buffer strip implementation were significantly associated with FCB concentration and load reductions. These results complement our findings for reductions of specific pathogens in runoff from these areas. These findings have practical significance because they document surface water quality benefits that the studied management practices provide in application on working farms and ranches. This direction is critical and timely for on-farm management efforts seeking to reduce microbial pollution in runoff and comply with indicator bacteria water quality criteria.

Key words | animal feeding operation, conservation practice effectiveness, critical area planting, fecal coliform bacteria, vegetative buffer strip

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INTRODUCTION

The impact of microbial contamination on water quality in coastal watersheds is an international concern. Programs such as the European Union's Water Framework Directive (CEC 2000, 2006) and Australia's National Water Quality management Strategy, including fresh and marine water quality guidelines (ANZECC 2000), are setting water quality criteria and directing water body assessment and mitigation. In the United States, similar action is being taken through

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Total Maximum Daily Loads (TMDLs). For example, the San Francisco Bay Regional Water Quality Control Board (CRWQCB) approved a pathogen TMDL for Tomales Bay in 2005 (CRWQCB 2005) and is now implementing a Conditional Waiver program for grazing lands (CRWQCB 2008). These policies established ambient water quality standards for FCB to protect beneficial uses of shellfish harvesting and contact and non-contact recreation in the watershed. The FCB standards are geometric means of 75 and 14 MPN/100 ml in tributary streams and bay water shellfish leases, respectively. The TMDL and Conditional Waiver also direct managers of FCB sources, including livestock agriculture operations, to implement management measures that will reduce FCB concentrations in storm water runoff from these operations.

Dairy farms and grazing livestock ranches commonly have designated high livestock use areas for the purpose of holding livestock during some portion of the year. These areas include exercise lots, sick pens, calving pens, calf corrals, feeding areas, and loafing areas. They are important production components for these dairies and ranches. For example, they provide lactating animals a place to exercise near milking facilities and facilitate cost-effective supplemental feeding. On these farms and ranches, sick pens, allow managers to monitor groups of animals that require direct and timely attention. The high stocking density and frequent heavy use of these areas results in relatively bare and compacted soils with limited infiltration capacity. This increases the susceptibility of these high use areas to accelerated runoff and pollutant transport capacity during winter storms, which can result in the delivery of manure, sediment and FCB to streams and coastal waters. In previous investigations, we found the highest FCB concentrations and loads in runoff coming from these high use areas in comparison to other dairy and ranch management units (Lewis *et al.* 2005). This finding is consistent with similar water quality findings from "farmyards" by Edwards *et al.* (2008) and for "steading" areas by Vinten *et al.* (2008).

The management challenge in these high use areas is to maintain animal productivity, health and welfare while complying with water quality regulations through the reduction of FCB mobilization and transport. Current steps producers take to meet this challenge include dry-season only use (April–October) to reduce the potential for hydrologic transport of fresh manure and FCB from these areas. Producers protect high use areas from stormwater run-on through the use of gutters and other storm drain networks. Finally, they scrape and remove manure from these surfaces in advance of winter storms. Even with such measures, high use areas still have the potential to deliver as much as ten fold more bacteria, nutrients, and sediment to surface waters in comparison to other management units (Lewis *et al.* 2005).

The objective of the management scale project reported here was to evaluate the effectiveness of management measures that provide soil surface protection cover and filter surface runoff on high use areas during winter rainfall-runoff events. Coupled with the management measures described above, we evaluated the additional reduction of FCB in runoff gained through annual implementation of soil cover and revegetation techniques (ABAG 1995; NRCS 2004; Raskin *et al.* 2005) in combination with vegetative buffer strips (NRCS 2004). As reviewed and referred to as "vegetative treatment systems" by Koelsch *et al.* (2006), these measures are being designed and implemented to improve the quality of runoff from open lots. Our specific objective was to implement practices that provide protective cover and filtering functions during winter rains to reduce erosion and transport of manure and sediment off of these areas to nearby receiving waters. We hypothesized that soil surface cover and buffer strip management measures would significantly decrease storm runoff FCB concentration and load from high use areas. This management scale investigation of these practices advances previous soil box and run-off plot investigations (Trask *et al.* 2004; Tate *et al.* 2006; Sullivan *et al.* 2007). The research presented in this paper complements previous investigations of *Giardia duodenalis* (Miller *et al.* 2007) and *Cryptosporidium* spp. (Miller *et al.* 2008) on the same coastal dairies and livestock ranches.

METHODS

Study location

The Tomales Bay Watershed is located approximately 64 kilometers north of San Francisco, California. It encompasses approximately 559 square kilometers divided among three main tributaries: Lagunitas, Olema, and Walker Creeks (Fischer *et al.* 1996). The Bay is approximately

19 kilometers long and less than 1.6 kilometers wide. Annual precipitation is 862 mm/year (standard deviation or SD = 312), occurring as rainfall predominately from October through May.

Agricultural production began in the watershed in approximately 1,850 and included dairying, livestock ranching, and row crop production such as potatoes. Row crop production declined in the early 1900s to less than 200 hectares of specialty crops today. Dairy farming and livestock grazing are still common in the watershed today. There are also records of a native oyster fishery as far back as 1890, with an even earlier use of the resource by native Americans. Commercial production of oysters began in 1918. Now approximately 280 hectares of leased bay tidal lands are in active production.

Five dairy farms were selected for this study based on voluntary participation and their location within the Tomales Bay watershed. Among the five cooperating dairies, 35 high use areas were enrolled as specific study sites.

Overall study design

This was an observational longitudinal study of a large cross-section of high use areas (Sample Size or $n = 35$) experiencing management scale implementation of measures designed to reduce FCB levels in stormwater discharge. Each high use area had one or more of the following management measures implemented during the study period: no management measures (control), soil surface cover (0 to 100%), winter livestock exclusion (yes, no), manure removal by scraping (yes, no), vegetative filter strip or treatment area (0 to 152 meters in length). The high use areas varied in size and slope (Table 1). FCB concentration, stormwater runoff rate, and FCB instantaneous load were determined for 351 sample events spread across these 35 study sites over 2 years (2002–2003 and 2003–2004). Multivariate analysis was used to determine associations between FCB levels discharged from high use areas and management measure implementation. The size, slope, stocking rate, animal age, curve number and hydrologic group (SCS 1985), and precipitation variables (24-hour and Annual cumulative) were treated as covariates to account for inherent area to area and storm to storm variation.

Management measure implementation

Soil surface cover

We adapted soil surface protection practices generally used for construction sites for implementation on bare soil surfaces typical of high use areas. These practices are designed to prepare sites in advance of the onset of winter storms and the associated potential for mobilization and

Table 1 | Rainfall, discharge, and management conditions of 35 dairy lots from which runoff samples were collected and analyzed during the 2002–2003 and 2003–2004 winter storm season

Lot Characteristic	Mean	Median	Min.	Max.
Precipitation and discharge				
24-Hour cumulative precip. (mm)	23	20	10	83
Annual cumulative precip. (mm)	388	481	37	713
Slope (°)	8.7	4	1	26
Instantaneous flow (m^3/sec)	0.009	0.002	0.00004	0.2
Storm runoff (hectare-mm)	13.0	8.1	0.0002	72.8
Management				
Size (hectare)	1.8	0.4	0.04	32.4
Stock number	50.7	30	5	390
Animal conc. (#/hectare)	83.8	46.6	0.7	308.9
Ground cover (%)	39.7	30.0	0	99.0
Buffer length (m)*	30.4	21	6	152.4

*Statistics describe conditions for the water quality improving management practices below 17 of the 35 studied lots.

transport of manure and FCB. The practices follow closely the USDA Natural Resources Conservation Service's (NRCS) critical area planting practice (NRCS 2004), and capitalizing upon documented reductions in raindrop impact and interrill erosion (Singer *et al.* 1981) and maintenance of infiltration rate (Singer & Blackard 1978) generated from straw cover of bare soil surfaces. Prior to first rains, a layer of straw is spread to provide cover during early winter storms. At the same time, the area is sown with grass seeding to provide ground cover during later winter storms after the straw has decomposed (Lennox *et al.* 2007). This treatment occurred in October of each study year on 11 of the 34 studied high use areas.

Annual barley grass (*Hordeum vulgare*) and Annual rye grass (*Lolium multiflorum*) were seeded due to their ability to tolerate compacted and marginal soils, and to provide soil cover for an extended period. Annual barley grass germinates and establishes quickly with minimal moisture and cool temperatures, thus providing soil surface cover during January and February. Annual rye grass established more slowly, providing soil surface cover from March to May. We spread straw at a rate of 5.4 metric tons/hectare and broadcast seeded 112 kg/hectare of annual barley and 28 kg/hectare rye grass across treated areas (Lennox *et al.* 2007). Soil surface measurement of percent bare ground, straw cover, annual barely grass cover, and annual rye grass cover were made once a month using a step point method (BLM 1996) in all 35 studied high use areas.

Livestock use and removal

In addition to seeding and straw application, we evaluated the ability of winter exclusion of cattle (26 areas) and scraping (removal) of manure prior to winter (28 areas), along with runoff treatments of vegetative buffer strips (14 areas), grassed waterways (2 areas), or impoundments (1 areas) to reduce FCB concentration and load.

Storm event sampling

It has been determined that excessive FCB loading to Tomales Bay is rainfall dependent (O'Connell *et al.* 2000; Lewis *et al.* 2005). This is consistent with findings from other systems along the Pacific Coast of North America (Shanks *et al.* 2006) and elsewhere (Kay *et al.* 2005) in which precipitation and storm runoff drive increased indicator bacteria values in tributary rivers and receiving bays. The California Department of Public Health uses 24-hour cumulative precipitation from a local precipitation station, Tomasini Point, to regulate harvest closures of winter shellfish growing leases in the Bay. Accordingly, we conducted storm-based water sampling and analysis of storm runoff for FCB below each study area.

Sample collection sites were identified for each high use are that captured all the runoff from a recruited high use area. Water samples for FCB concentration determination were collected via grab sampling. Samples were collected from each ranch and respective sample location during selected storms (2 to 6) across the entire season. Generally, the relatively flashy nature of runoff from these areas prevented collection of a series of samples during each storm via grab sampling. In a few instances this was achieved. At each sample collection site for each water sample collection event, instantaneous runoff was measured using either the area-velocity method (velocity × channel width × channel depth × 0.85 to account for surface flow) (Mosley & McKercher 1993) with a Global Waters flow meter (Global Waters Inc., Gold River, California, USA) or the time to fill a container of known volume. Method used was dependent upon have a cross-sectional area of the running water sufficient to accommodate the flow meter.

Fecal coliform bacteria enumeration

Each sample was collected in sterile sample bottle and shipped overnight at 4 to 10°C to the School of Veterinary Medicine, University of California, Davis, California. Given the uncertainty in expected FCB concentration, a range of three to five 10 or 100-fold serial dilutions were constructed and analyzed from each sample. For each dilution, 50 ml was filtered through a 47 mm, 0.45 μm pore sterile filter (Millipore, Billerica, MA), incubated on mFC agar (Difco agar by Becton Dixon Company, Sparks, MD) at 44.5°C, and enumerated for FCB after 24 hours (APHA 1995).

Storm-based sampling resulted in different holding-time between sample collection and processing. As a consequence, significant variation was potentially introduced to the overall dataset due to variable holding times within and between storm events. In order to adjust FCB enumerations to a standard 24-hour holding time, we conducted a FCB decay curve analysis (Tate *et al.* 2006). Twenty-two water samples were collected from different sources (control watershed, upstream and downstream of different locals dairies, runoff from pastures or lots, and from waste management system) and at different times, with FC concentration determined daily for six days. These 122 data points were $\log_{10}$-transformed and a linear mixed-effects model was fitted to the data, with time (hr) and water source as the fixed effects, water sample ID the group variable, and a power variance function used to control unequal variance (Pinheiro & Bates 2000).

In order to adjust the FCB concentration in each water sample tested x hours ($t = x$) after initial time of collection ($t = 0$) to a single 24-hour standard ($t = 24$), we first assumed the following basic model (Tate *et al.* 2006),

$$\log_{10}(\text{Fecal coliform}_{t=x}) = \log_{10}(\text{Fecal coliform}_{t=0}) + \beta(t = x) \quad (1)$$

whereby $\log_{10}(\text{fecal coliform}_{t=x})$ is the observed $\log_{10}$ concentration of FCB determined x hours ($t = x$) after initial time of collection, $\log_{10}(\text{fecal coliform}_{\,t=0})$ is the modeled $\log_{10}$ concentration of FCB at the initial time of collection ($t = 0$), and $\beta(t = x)$ is the fitted decay coefficient(s) generated by the linear mixed effects model described above. $\beta(t = x)$ is allowed to be a univariate or polynomial term depending on whether the raw data signifies a first or second-order time-dependent decay process for the FCB concentration in our source water. The decay process is for water samples held at approximately 4°C. Once $\beta(t = x)$ is obtained, Equation (2) is used to adjust each sample to a single 24-hour standard ($t = 24$), which is derived as follows,

$$\text{Fecal coliform}_{t=24} = (\text{Fecal coliform}_{t=x})10^{\beta(24-x)} \quad (2)$$

whereby fecal $\text{coliform}_{t=24}$ is the fitted or expected concentration of FCB at a 24-hour standard, fecal $\text{coliform}_{t=x}$ is the observed concentration of FCB determined x hours ($t = x$) after initial time of collection, and $10^{\beta(24-x)}$ is the expected decay coefficient adjustment factor raised to the power of 10 which allows us to model concentrations of FCB directly instead of $\log_{10}$ concentration values.

The $\log_{10}$ concentration of FCB followed a first order decay process, such that $\beta(t) = -0.0022$ with units of time set in hours (95% CI, -0.003, -0.0014). This decay coefficient did not vary significantly across the different sources of water (P-value > 0.05 for an interaction term between time and water source), indicating that a single decay coefficient can be used for adjusting FCB concentrations at $t = x$ to a 24-hour standard ($t = 24$).

Instantaneous load calculation

Using FCB concentration and instantaneous runoff rate for each sample event, we calculated instantaneous load of FCB for each loading unit, defined as:

$$\text{instantaneous load(cfu/sec/hectare)} = \frac{(\text{cfu}/100\,\text{ml})(10^6\text{ml/m}^3)(\text{m}^3/\text{sec})}{(\text{total surface area of loading unit in hectares})} \quad (3)$$

where (cfu/100 ml) is the FCB concentration in the water sample and (m^3/s) is the instantaneous runoff rate associated with that water sample. This calculation is necessary in order to compare between study areas on a standardized basis of per unit time and per unit area.

Statistical analysis

Linear mixed effects regression was used to test for differences in FCB concentration and instantaneous load for high use areas with differing combinations of management measures (Pinheiro & Bates 2000). Unique models were developed for FCB concentration and instantaneous FCB load. FCB concentration and instantaneous load were set as the outcome variables, with each high use area set as a group effect to adjust the p-values for repeated sampling at the same sites. A forward stepping approach was used to develop the multivariate regression model, with $P \leq 0.05$ set as the criterion for inclusion of the variable in the final model.

RESULTS AND DISCUSSION

A total of 351 samples were collected from various high use areas, including 194 during 2002–2003 and 157 during 2003–2004 water years. Geometric mean FCB concentration for the entire dataset was 7.3e + 06/100 ml and ranged from 1,351 to 5.48e + 017 cfu/100 ml. Geometric mean FCB instantaneous load for the entire dataset was 4.1e + 0.08, ranging from 177 to 1.93e + 019 cfu/hectare/sec.

The relationship between both climatic and management factors and FCB results were highly variable. In the case of cumulative precipitation, FCB concentrations ranged from 1.00E + 03 to 1.00E + 18 at lower values of rainfall (Figure 1). This variability reduces, evidenced by the smaller ranges in FCB concentration associated with cumulative precipitation of greater than approximately 300 mm. In a similar manner, the range and variability in FCB concentration decreases relative to percent ground cover increases (Figure 2).

Modeling results document that both FCB concentration and instantaneous load were significantly related to 24-hour and annual cumulative precipitation, percent slope, the practices of scraping and winter use, site mulching and seeding, and vegetative buffer strip length. Factors not found to be significant were size of the high use area, stocking number, curve number and hydrologic group (SCS 1985). Animal age was found to be significant, but it was also multicollinear with winter use of lots given the fact that calves are not provided access to open lots regardless of season. Hence, all calves were coded as no winter lot use which created the multicollinearity condition, making it difficult to statistically separate these two collinear effects on FCB concentration and instantaneous load.

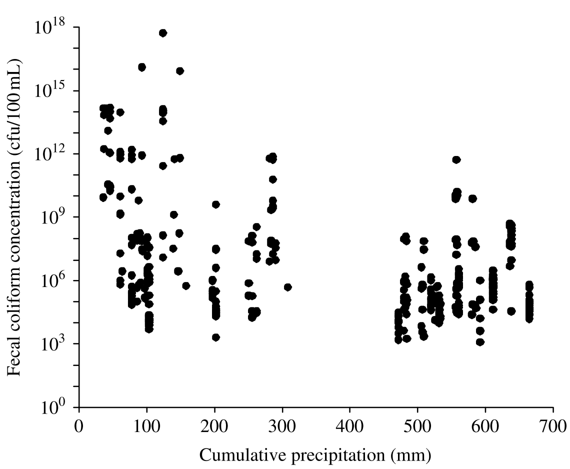

Figure 1 | Individual sample results for fecal coliform concentration as a function of cumulative precipitation.

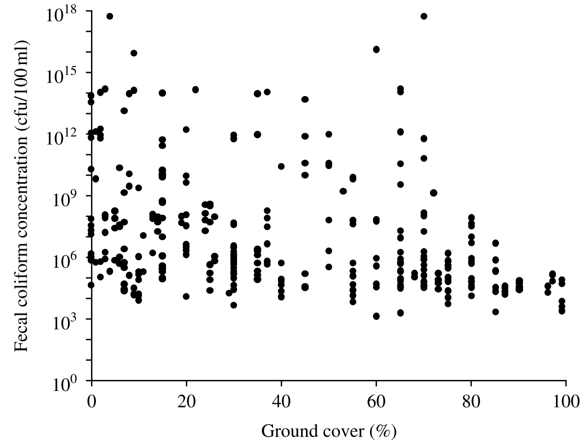

Figure 2 | Individual sample results for fecal coliform concentration as a function of percent ground cover.

The baseline water quality conditions, modeled as the constant coefficients (or intercept term) for FCB concentration and load in high use area runoff from our regression models, were approximately 61,700 cfu/100 ml (Table 2) and 478,630 cfu/hectare/sec (Table 3), respectively. Using our data derived models to generate predictions, these constants for FCB concentration and instantaneous load represent the baseline referent conditions that are then potentially influenced or modified by climatic factors, site conditions, and management practices. To demonstrate, at a median value of 20 mm for 24-hour cumulative and 481 mm of annual cumulative precipitation, the model predicts that FCB concentration and instantaneous load in runoff would be 10,378 cfu/100 ml and 273,771 cfu/hectare/sec, respectively.

The concentration and load of FCB in storm runoff from the studied high use areas had complex associations with precipitation. On a storm or 24-hour basis, increasing precipitation was associated with an increased FCB concentration and load. This is represented by the respective positive coefficients for 24-hour precipitation in the concentration (Table 2) and load (Table 3) models. There was also a smaller negative quadratic coefficient in each model for the relationship with 24-hour precipitation and FCB. For example, as 24-hour cumulative precipitation was

Table 2 | Linear mixed effect regression model for the associations of management practices, slope, and rainfall with fecal coliform concentration (log_{10} value) in surface runoff from dairy lots during storm conditions, 2002–2004, Tomales Bay, California

Factor	Coefficient	95% CI*	*P*-value*
Constant or intercept term for the model	4.79	(2.90, 6.67)	< 0.0001
24-hour precipitation (mm)	0.19	(0.12, 0.26)	< 0.0001
24-hour precipitation^2 (mm)^2	−0.003	(−0.004, −0.002)	< 0.0001
Cumulative precipitation (mm)	−0.015	(−0.02, −0.009)	< 0.0001
Cumulative precipitation^2 (mm)^2	0.00002	(0.00, 0.00)	0.0016
Slope (%)	0.067	(0.003, 0.13)	0.04
Scraped	1.75	(0.67, 2.84)	0.0017
Winter use	2.24	(1.42, 3.08)	< 0.0001
Length of vegetated buffer (m)	−0.022	(−0.04, −0.003)	0.0238
Percent ground cover (%)	−0.014	(−0.03, −0.003)	0.0105

*Adjusted for potential lack of independence due to repeated sampling of lots across storms.

Table 3 | Linear mixed effects regression model for the associations of management practices, slope, and rainfall with fecal coliform load (log_{10} value) in surface runoff from dairy lots during storm conditions, 2002–2004, Tomales Bay, California

Factor	Coefficient	95% CI*	p-value*
Constant or intercept term for the model	5.68	(3.77, 7.61)	< 0.0001
24-hour precipitation (mm)	0.22	(0.15, 0.29)	< 0.0001
24-hour precipitation^2 (mm)^2	−0.003	(−0.005, −0.002)	< 0.0001
Cumulative precipitation (mm)	−0.013	(−0.02, −0.006)	0.0001
Cumulative precipitation^2 (mm)^2	0.000012	(0.00, 0.00)	0.0094
Slope (%)	0.08	(0.01, 0.15)	0.0181
Scraped	1.83	(0.72, 2.94)	0.0013
Winter use	1.99	(1.42, 3.08)	< 0.0001
Length of vegetated buffer (m)	−0.029	(−0.05, −0.009)	0.0042
Percent ground cover (%)	−0.015	(−0.03, −0.004)	0.0089

*Adjusted for potential lack of independence due to repeated sampling of lots across storms.

increased from 0 to ~32 mm, FCB concentration and load likewise increased, but once 24-hour cumulative precipitation exceeded 32 mm, further increases in precipitation amounts were associated with reductions in FCB concentration and load (Figure 3).

Model results also indicate that increases in cumulative precipitation were associated with decreases in FCB concentration (Table 2) and load (Table 3 and Figure 4). However, because of the positive quadratic coefficient for annual cumulative precipitation in both the concentration and load models, observed decreases reverse and begin to increase once annual cumulative precipitation exceeded 525 mm of precipitation.

Increases in microbial pollutant recovery associated with increases in precipitation have been document previously (Trask *et al.* 2004; Tate *et al.* 2006). Our observations of increases in loads and concentrations up to the point of ~32 mm in 24-hours, with decreasing FCB values thereafter, is indicative of storm flushing or the increased transport of available FCB until that source is removed. Similarly, the continued decrease in concentration and load with increases of annual cumulative precipitation up to 525 mm suggests annual flushing or transport of fecal bacteria from a source that is not constant. We documented similar flushing relationships with annual and 24-hour cumulative precipitation for *Giardia*

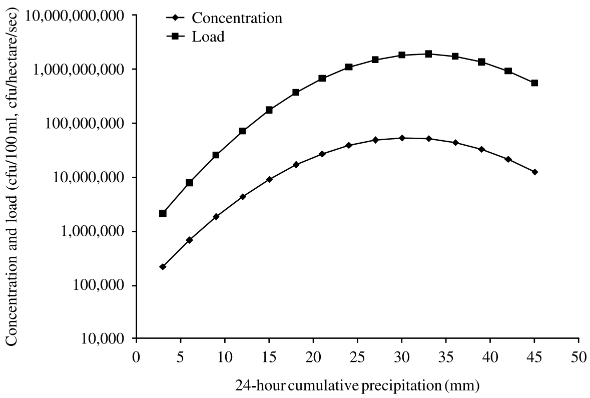

Figure 3 | Modeled relationship of fecal coliform concentration and instantaneous load as a function of 24-hour cumulative precipitation.

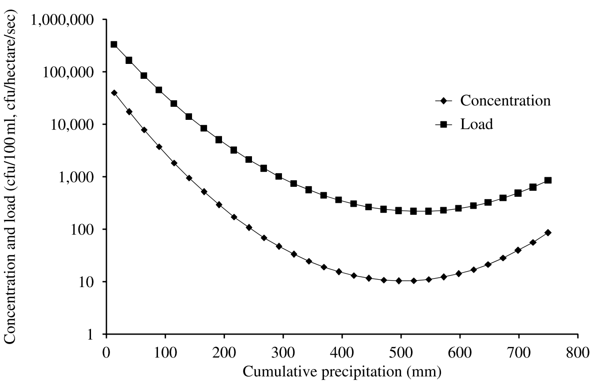

Figure 4 | Modeled relationship of fecal coliform concentration and instantaneous load as a function of cumulative precipitation.

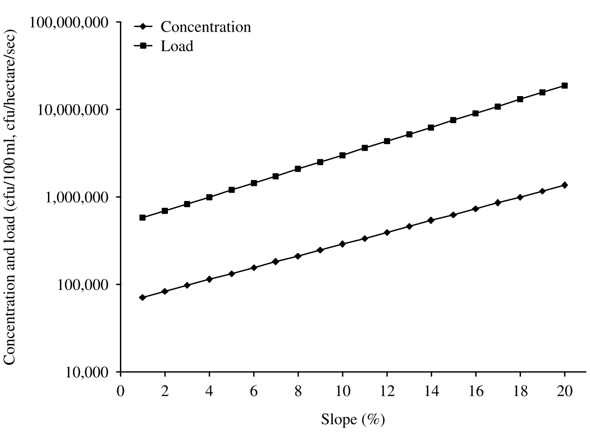

Figure 5 | Modeled relationship of fecal coliform concentration and instantaneous load as a function of high use area slope.

duodenalis (Miller *et al.* 2007) and *Cryptosporidium* spp. (Miller *et al.* 2008) concentrations and loads at these same sites.

Increases in percent slope were associated with increases in storm runoff FCB concentration and load (Figure 5). For each one percent increase in site slope, there was an associated increase of FCB concentrations and load of 14,000 cfu/100 ml and 140,000 cfu/hectare/sec, respectively. This result is similar to those documented in earlier studies (Trask *et al.* 2004; Tate *et al.* 2006) and also consistent with established soil erosion models such as the Modified Universal Soil Loss Equation (Renard *et al.* 1994). Increased slope reduces the volume of water infiltrated into the soil and increase the volume of water in runoff thus increasing the entrainment and transport potential for sediment and manure. It is uncommon for a farmer to select a high use area location with a slope approaching or greater than 10 percent because these are not conducive to livestock management objectives. Conversely, the hilly topography of the study area precludes finding sites with zero slope. However, our results indicate that careful site selection to reduce the site grade by even one or two percent may generate marked improvements to water quality. Interestingly, we did not find a similar relationship for slope and the concentration or load of *Giardia duodenalis* (Miller *et al.* 2007) or *Cryptosporidium* spp. at similar study locations (Miller *et al.* 2008). In contrast, using soil boxes dosed with predetermined pathogen amounts to simulate in-field vegetated buffer strips, similar flushing effects were documented for *Cryptosporidium* spp. (Tate *et al.* 2006). This comparison between our observational management scale study and other controlled, experimental studies highlights the increased variability in the timing and location of FCB and fecal pathogen sources on working farms.

Studied management practices had varying positive and negative associations with storm runoff FCB concentration (Table 2) and load (Table 3). Winter use compared with no winter use was associated with a large amount of FCB discharging in the runoff from these sites. Using our regression models to generate water quality predictions and setting 24-hour and cumulative precipitation to levels of 20 and 482 mm, respectively, predicted FCB concentration would be 1,815,574 cfu/100 ml and FCB load would be 27,032,051 cfu/hectare/sec from areas with winter use.

These values represent differences of more than two orders of magnitude in comparison to no winter use. Mankin *et al.* (2006) documented similar improvements to water quality when cattle were not present on feedlots. A milking dairy cow is estimated to deposit 68 Kg/day wet weight manure (ASAE 2005), with a typical FCB concentration of 10^6 cfu/g (Kouznetsova *et al.* 2007). The result is a total daily deposit of 68 billon bacteria per cow. Multiple that by 100 cows, accessing a high use area, and the total daily load surpasses six trillion. If only five percent of this load is eroded and transported during a single storm, the result is 340 billon. While FCB fate and transport is much more complex than this calculation, it demonstrates the potential FCB available for transport and how no winter use is associated with reduced FCB concentration and load. It is important to point out for planning and implementation purposes that reducing winter use on the studied high use areas requires an available loafing barn and manure management system to capture waste during the winter months. To make such improvements, a correspondingly significant capital investment is needed to either expand existing infrastructure or to design and build anew.

The practice of scraping had a positive association with FCB concentration and load. Model results indicated that FCB concentration and load in runoff from a scraped high use area, under the median 24-hour and annual cumulative precipitation conditions, might approach 155,367 cfu/100 ml and 18,540,695 cfu/hectare/sec, respectively. This is counter intuitive given the practice removes the upper centimeters of manure that have accumulated during the previous dry season. Until we can verify the causal mechanisms associated with scraping and elevated bacterial counts from these lots, we are uncomfortable making the recommendation to cease scraping of these high use areas. One consideration is that annual surface scrapping has removed topsoil and any remaining groundcover to reveal loosely unconsolidated subsoil laden with indicator bacteria. Soil mean fecal coliform concentration in the top 10 cm of these areas was 4,316 cfu/g (SE = 1,880, $n = 12$) compared with 62 cfu/g (SE = 37, $n = 13$) from 10 to 30 cm below the surface. We did not anticipate this result and as a consequence we did not design the study to fully evaluate scraping verse no-scraping separate from the other practices.

Length of vegetative buffer was negatively associated with FCB concentration and load (Tables 2 and 3). The result is a relationship wherein concentration and load decrease as buffer length increases (Figure 6). Each additional meter of buffer was associated with a reduction in FCB concentration and load of more than 2,900 cfu/100 ml and 29,000 cfu/hectare/sec, respectively. These reductions are consistent with those we documented for *Giardia duodenalis* (Miller *et al.* 2007) and *Cryptosporidium* spp. (Miller *et al.* 2008).

The benefits of vegetative buffer strips to reduce microbial pollution in surface runoff have been demonstrated in other dairy and livestock agriculture production systems (Bedard-Haughn *et al.* 2005; Tate *et al.* 2006; Sullivan *et al.* 2007). However, there is limited research on their efficacy to improve water quality below animal feeding areas (Koelsch *et al.* 2006). Examples of research include investigations of benefits below manure piles (Fajardo *et al.* 2001) and pastures (Lim *et al.* 1997; Sullivan *et al.* 2007).

The FCB concentration and load reductions associated with these practices in application on working farms were less than those observed using idealized soil box and runoff plot simulations (Fajardo *et al.* 2001; Tate *et al.* 2006; Sullivan *et al.* 2007). This is most likely due to the lack of infiltration and sedimentation because of channelized flow typical of these small drainage canals or ditches at these dairy locations. Both slope and length are driving factors for buffer efficacy and design (Koelsch *et al.* 2006), and the complex slopes in the study area reduce the number of locations where strips can be installed and also restrict their

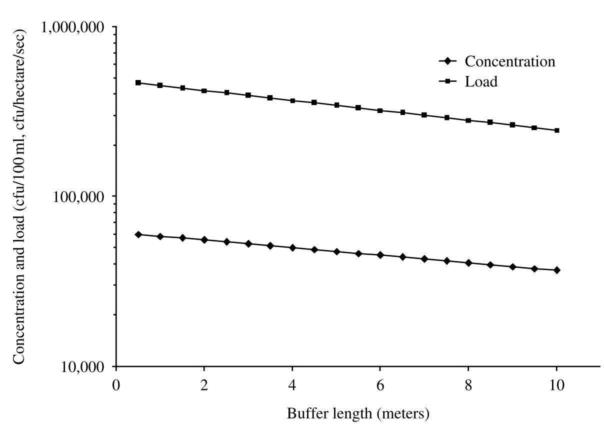

Figure 6 | Modeled relationship of fecal coliform concentration and instantaneous load as a function of vegetative buffer length below a given high use area.

length. The vegetation management required to maintain a strip's annual growth cycle, and therein its ability to improve runoff through sedimentation and infiltration (Bedard-Haughn *et al.* 2005; Koelsch *et al.* 2006), may not always be the highest priority for the farmer. It is because of these considerations that many of the vegetated treatment systems we studied were vegetated channels or ditches lacking the sheet flow most desired for maximum reduction of pollutants in runoff (Koelsch *et al.* 2006).

The combination of straw mulch and grass seeding resulted in over 75 percent ground cover of treated areas from November through March (Lennox *et al.* 2007). In the first two months the straw mulch provided the greatest cover. As it decomposed and the grasses grew, the greatest ground cover was provided by barley grass in December and January and then by the rye grass in February and March. The resulting relationship to water quality is that increases in ground cover were associated with decreasing FCB concentration (Table 2 and Figure 7) and load (Table 3 and Figure 7). For example, for every 10 percent increase in ground cover, FCB concentration and load were reduced by more than 12,000 cfu/100 ml and 99,000 cfu/hectare/sec, respectively.

Seeding and mulching high use areas on an annual basis has additional labor and materials costs for the farmer. Perhaps this cost is not prohibitive considering that the high use areas studied occupied on average 1.2 hectares. However, a few select sites had areas of 10, 12, and even 32 total hectares on one farm. Additionally, there is the potential for competition of labor from other farm activities at the appropriate time to treat these high use areas. Care should be given to avoid potentially blocking storm drains, downstream of these areas, caused by storm runoff transport of straw during storms. With these precautions in mind, the practice of critical area planting provided a protective groundcover, preventing raindrop impact and associated mobilization, leading to reductions in not only FCB concentration and load, but also *Cryptosporidium* spp. (Miller *et al.* 2008). Interestingly, we did not document reductions for *Giardia duodenalis* concentration or load (Miller *et al.* 2007) associated with ground cover. This may have resulted because of pathogen specific fate and transport dynamics (Berry *et al.* 2007) or the fact that most of the on-farm environmental loading of *Cryptosporidium* spp. was limited to runoff from calf hutches which were typically located on concrete surfaces and not soil surfaces conducive to straw mulching and seeding.

To demonstrate how the climatic and site conditions were integrated with implementation of the studied management practices, we used our regression model to predict FCB runoff concentration scenarios (Figure 8). One worst case scenario based upon our model would be the first storm of the year with 24-hour value of 12.5 mm. This amount was selected because it is the 24-hour cumulative value that triggers closure of shellfish harvesting leases in Tomales Bay (Commandatore 2007).

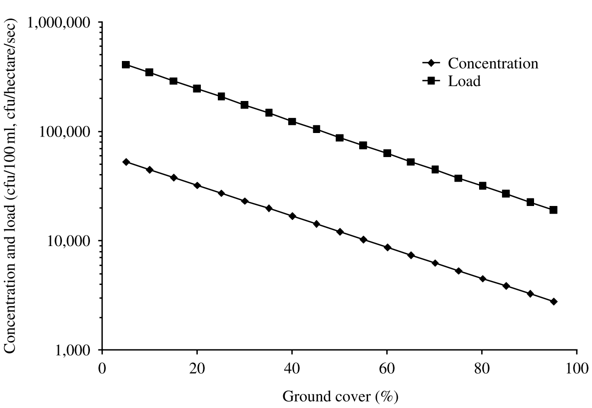

Figure 7 | Modeled relationship of fecal coliform concentration and instantaneous load as a function of the percent ground cover resulting from seeding and mulching a high use area.

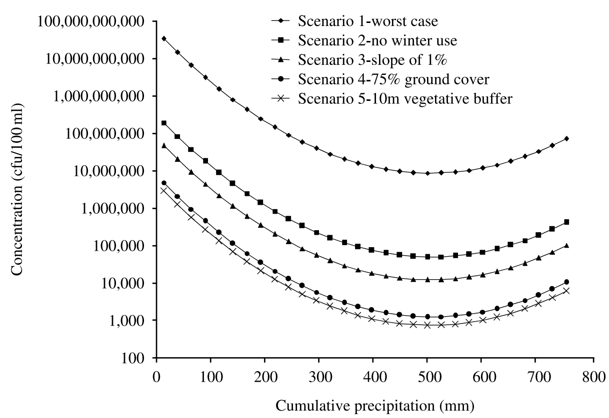

Figure 8 | Modeled fecal coliform concentration as a function of cumulative precipitation for management practice scenarios with 24-hour cumulative precipitation held constant at 12.5 mm. The worst case scenario is for a high use area that includes winter use, is on an area with a 10% slope, has only minimal ground cover of 5%, and has no vegetative buffer strip below it. Management practice implementation for each successive scenario is additive and indicated by the legend. For example, Scenario 3 represents a high use area with a slope of 1% and no winter use.

This worst-case scenario is also a high use area that was scraped, used in the winter, had a 10% slope, ground cover of 5%, and no vegetative buffer strip. Subsequent scenarios of improved water quality would be no winter use in Scenario 2, locating the area on a low (1%) slope in Scenario 3, providing 75% ground cover in Scenario 4, and implementation of a 10-meter vegetative buffer in Scenario 5. Removal of winter use was predicted to be associated with a $>99\%$ reduction or >33 billon cfu/100 ml from a high use area under worst case scenario conditions. With all studied management practices implemented, the resulting FCB concentration was reduced to 2.9 million cfu/100 ml. While the predicted percent reduction in concentration was only 0.5% when the slope of a lot was reduced from 10% to 1%, the potential total reduction was >145 million cfu/100 ml. Similarly, increasing ground cover to 75% is predicted to result in a 0.1 percent change from worst case scenario and a reduction of >43 million cfu/100 ml. Implementation of a 10 meter vegetative buffer strip reduced FCB concentration by only 0.006% from worst case conditions, but results in total potential reduction of >0.9 millon cfu/100 ml.

CONCLUSIONS

Reducing FCB in runoff from dairy and ranch high use areas is a complex decision that needs to take into account the role that climate, site characteristics, and management practices have in influencing bacterial concentrations and loads. Our results indicate that there are storm and annual flushing dynamics in association with precipitation. This is indicative of a source that is not constant on either a storm or annual basis. Therefore, management and implementation of practices that improve water quality and reduce the transport of FCB need to address the potential for FCB transport during early and large storm events.

The highest storm runoff FCB concentrations tended to occur during early season storms and in November and December. These FCB waterborne concentrations were likely higher than levels found in fresh bovine feces (Kouznetsova *et al.* 2007), suggesting suggests that one or more of the species that comprise the FCB group, such as *Klebsiella* sp., may have grown in the fecal-soil surface prior to the runoff event. Late fall or early winter wetting of surface soils followed by midday warming likely stimulates growth for many of these bacterial indicator species.

Results from our regression models for FCB concentration and load in high use area runoff indicate that improvements to water quality can be obtained through multiple management measures. The values in Scenario 5 (Figure 6) represent the greatest or "optimal" benefits to water quality that can be gained from combining studied management practices, assuming that these beneficial management practice function independently from each in generating their water quality benefits. The greatest reduction to both concentration and load was predicted to occur by a reduction in winter use, followed by placement of these areas on relatively level ground. Additional gains can be made by seeding and covering areas in advance of winter, and by installing vegetated filter strips. Though these "optimal" benefits are dairy and site specific because each farm is a unique agricultural system, our results offer realistic management alternatives for conservation planning. However, as discussed, each of the studied practices is not without other impacts and trade-offs to the functionality and profitability of the farming system which should be taken into consideration.

Controlled experiments have documented the benefits of the studied practices to reduce microbial pollution in surface run-off from livestock agriculture (Koelsch *et al.* 2006; Tate *et al.* 2006; Sullivan *et al.* 2007). Combining our management scale study results for FCB, *Giardia duodenalis* (Miller *et al.* 2007), and *Cryptosporidium* spp. (Miller *et al.* 2008), we document the influences that studied practices have on water quality under working farming operations and uncontrolled climatic conditions. This has practical significance to the regulated and regulatory communities striving to safeguard human health from fecal-borne pathogens and implement solutions for complying with water quality criteria based upon indicator bacteria.

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