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Soil Nutrient Load and Drain Water Quality in Seepage Fields Receiving Milk House Wastewater

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Abstract The large volume of wastewater generated on dairy farms from the cleaning of milk pipelines and milking equipment contains nutrients and microorganisms that could pollute waterways if discharged without treatment. The objective of this study was to evaluate a modified septic tank-seepage field system for disposing of milk house wastewater, by measuring the accumulation of nutrients in the soil and monitoring the water drained from the seepage field. The study was conducted on two small dairy farms (40–50 milking cows) in south-west Québec, Canada. After passing through a sediment and milk fat trap and then the septic tank, the milk house wastewater was drained into a 0.45 ha experimental seepage field under pasture or arable cropped land. Much larger than a conventional seepage bed (0.025 ha), the experimental seepage field was designed to remain recycle the wastewater nutrients and water, while preventing soil saturation. Annual nutrient loading from milk house wastewaters were, on average, 60 kg total N ha^{-1}, 50 kg total P ha^{-1} and 80 kg total K ha^{-1}. The concentrations of plant-available nutrients increased when milk house wastewater entered the seepage field, but the magnitude of change was farm-specific, due to the unique topography and soil characteristics offered by each farm. For instance, the P concentration was unchanged on one farm, but there was rapid and significant accumulation of P in the 20–60 cm depth of the soil profile on the second farm. There was an increase in Ca and Mg concentrations in the soil profile on both farms, but soil salinity remained <4 dS m^{-1} during this study. Water drained from the experimental seepage fields was similar in quality to that drained from a control area, indicating that the seepage fields were sufficiently large to adsorb and treat the nutrients contained in milk house wastewater in the short-term. Assessment of the cation and anion adsorption capacity of soils on these farms will be necessary to verify the treatment capacity and effective lifespan of the seepage fields.

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1 Introduction

The cleaning of milking equipment on dairy farms generates an estimated 15 to 20 l of milk house wastewater per cow each day (Urgel Delisle et Ass.

Inc., 1994). Milk house wastewater contains an organic load that can create a biological oxygen demand (BOD_5) of 300 to 10,000 mg l^{-1}, as well as soluble nutrients, from 5 to 625 mg NH_4-N l^{-1} and 6 to 183 mg l^{-1} of total phosphorus (Jamieson, Gordon, Cochrane, Madani, & Burney, 2002; Loerh, 1983). If discharged into waterways without treatment, milk house wastewaters pose a threat to water quality.

In response to these potential risks, the Quebec Ministry of Environment imposed regulations in 2001 that obliged all dairy farms to desist from discharging milk house wastewater without treatment. On dairy farms with a liquid manure handling system, milk house wastewaters are simply used to make manure slurries for land disposal, but farms with a solid manure handling system were expected to construct a facility to store and treat their milk house wastewater. A number of technologies, such as artificial wetlands, reverse osmosis, aerobic reactors and anaerobic digesters, are available for wastewater treatment (Craggs, Tanner, Sukias, & Davis-Colley, 2003; Luostarinen & Rintala, 2005; Newman, Clausen, & Neafsey, 2000; Reimann, 1997; Schaafsman, Baldwin, & Steb, 2000). Besides being expensive or requiring a large herd number (more than 100 cows) to justify the investment and operating costs, most of these systems do not permit on-farm recycling of nutrients and water. Instead, they represent an 'end-of-pipe' treatment to clean the water before it is discharged into a water course.

The goal of this study was to evaluate an economical and low maintenance technology for small dairy farms that would provide for the better recycling of nutrients and water from milk house wastewater. Many small dairy farms in Quebec treated their milk house wastewater with a conventional septic tank system, but discharged the treated wastewater into a ditch because their seepage field tended to become clogged due to the accumulation of milk fat inside and the saturation of the soil around the sewer pipes (Urgel Delisle et Ass. Inc., 1994). Morin, Lemay, Ali, and Barrington. (2004) modified the septic tank system for treating dairy milk house wastewater by installing a sediment and milk fat trap before the septic tank and enlarging the seepage field. The trap was designed to facilitate the removal of milk fat and sediments susceptible of accumulating and overloading the septic tank. It had the capacity to retain the wastewater produced during one milking, thus allowing for the cooling and hardening of the milk fat and the settling of sediments. The seepage field was enlarged from 0.025 ha to 0.45 ha to reduce risks of soil saturation and loss of permeability, and covered enough cropped land that water and nutrients could be taken up by pasture or arable crops during the growing season. Finally, the enlarged seepage field was drained by a subsurface system installed between and slightly deeper than the runs of sewer pipe, to control the ground water table and force the soil to filter the wastewater. Our working hypothesis was that the enlarged seepage field was sufficiently large to adsorb nutrients contained in the milk house wastewater and the risk of environmental pollution from this system would be minimal.

The objective of the project was to therefore to evaluate the performance of this modified septic tank-seepage field system for treating milk house wastewater, by measuring the accumulation of nutrients in the soil and by monitoring the quality of the water drained from the seepage field.

2 Experimental

2.1 Experimental farms and their septic tank-seepage field systems

Two dairy farms, located southwest of Montréal, Quebec, Canada (45°28′ N, 73°45′ W) were selected for this project because they already had septic tank installations. However, seepage fields were enlarged to about 0.45 ha on each farm to bypass the existing clogged seepage field. The size and general operations of Farms MH-1 and MH-2 are described in Table I. On both farms, the seepage field was built in a pasture, next to the dairy cow barn. Soils were classified as mixed, frigid Typic Endoaquents. The seepage field of Farm MH-1 had a relatively flat topography, sloping away from the barn at a rate of 0.5%; the soil profile consisted of 1.5 m of silt overlaying marine clay. On Farm MH-1, the surface soil (0–20 cm) was a silty loam of the Norton series containing 170 g sand kg^{-1} and 180 g clay kg^{-1} with pH 6.7 and 25 g organic C kg^{-1}. The seepage field on Farm MH-2 sloped away from the barn at a rate of 1%; the soil profile varied in texture from gravely silty clay at the top to a silty loam at the bottom of the slope. The surface soil was a silty loam of the St-Anicet series

Table I Description of the two dairy experimental farms

Description	Farm MH-1	Farm MH-2
Number of cows	40	50
Type of enterprise	Organic	Conventional
Cow breed	Holstein and Jersey	Holstein
Manure management	Piled directly on the soil	Manure platform for solid and seepage accumulation
Septic tank size, m^3	3.4	3.4
Milk butter fat, %	4.0	3.5
Pipe line capacity, cows	32	42
Soap addition for equipment washing	Manual	Manual
Soap used for equipment washing, ml d^{-1}	Phosphoric acid: 315 Chlorinated detergent: 420	Phosphoric acid: 315 Chlorinated detergent: 420 Antiseptic soap: 120
Other water treatment		Water softener : 250 to 300 kg y^{-1} of salt
Well water quality		
TN, mg l^{-1}	0.2	0.15
TP, mg l^{-1}	ND	ND
TK, mg l^{-1}	6.8	3.4
pH	7.2	7.5

ND Not detected

containing 180 g sand kg^{-1} and 220 g clay kg^{-1} with pH 7.4 and 42 g organic C kg^{-1}.

In early July 2003 and on each farm, a sediment and milk fat trap (Figures 1 and 2) was installed before the existing septic tank. The trap was a reinforced concrete manhole with an inside diameter of 0.61 m and a depth of 1.5 m, giving a wastewater holding capacity of 440 l. This capacity slightly exceeded the volume of wastewater produced during one milking, estimated to be 7.5 l cow^{-1} per milking or 15 l cow^{-1} d^{-1}. The trap's T-shaped outlet pipe was designed to prevent the milk fat from flowing into the septic tank. Each trap was equipped with a concrete cover that could easily be pushed aside to remove the accumulated milk fat and sediments using a sewer spoon.

A new seepage field was also built on each farm, in early July 2003. The seepage field was built by first installing three runs of sewer pipe at a spacing of 15 m (Figures 3 and 4); each sewer pipe run measured 100 m in length, and was installed at 0% slope and a depth of 550 to 700 mm. The ABS sewer pipes had an inside diameter of 75 mm and were perforated with 12 mm holes spaced at every 305 mm. Because of the silty texture of the soils on both farms, a geotextile was manually installed around the sewer pipes to prevent the

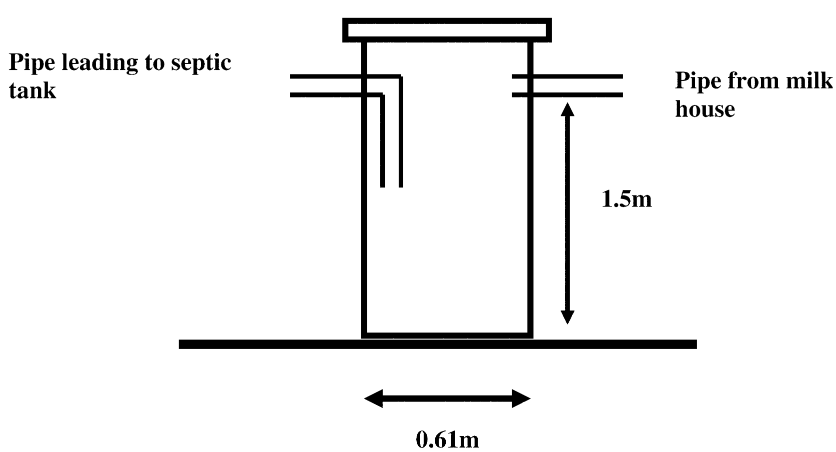

Figure 1 Description of the sediment and grease trap.

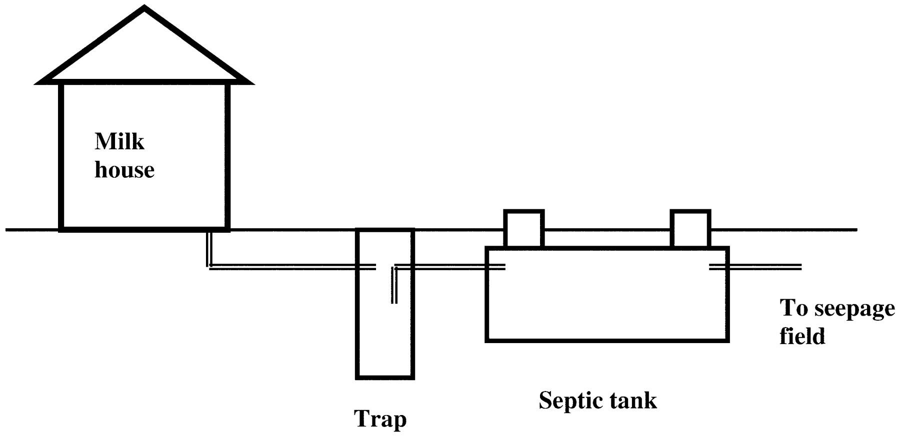

Figure 2 Typical trap and septic tank installation on both dairy farms.

entry of soil into the sewer pipes. To maintain 0% slope in spite of the natural ground topography, the sewer pipes were installed parallel to the contour lines, as much as possible, and a 2.4 m section of sewer pipe was installed at a sharp slope, at one or two places along the full 100 m length, between sections with 0% grade. All sewer pipes were installed directly on the soil, without using a bed of crushed stone, to reduce construction costs. To keep the seepage field well drained, a subsurface drainage pipe (perforated corrugated polyethylene tubing with an inside diameter of 100 mm) was installed between and 150 mm deeper than the sewer pipes. The subsurface drainage pipe followed the natural topography of the site. Draining into a nearby ditch, this subsurface drainage system controlled the water table height and forced the wastewater to seep into the soil.

The seepage field on farm MH-1 was used as a pasture for cattle during 2003, but in 2004, the producer cultivated the field with a disk harrow (10 cm depth) and seeded it with mixed cereals (*Triticum aestivum* L., *Hordeum vulgare* L. and *Avena sativa* L.) for animal forage. The seepage field on Farm MH-2 was used as a pasture by dry cows and heifers from May to October of 2003 and 2004.

2.2 Volume of milk house wastewater, water sampling and analysis

The volume of milk house wastewater generated on each farm was estimated by taking monthly readings from a meter installed on the water line entering the milk house and assuming that water use represented the amount of wastewater generated. The pH and nutrient concentrations (TN, TP and TK) of well water entering the milk house on each farm are reported in Table I. Milk house wastewater volume

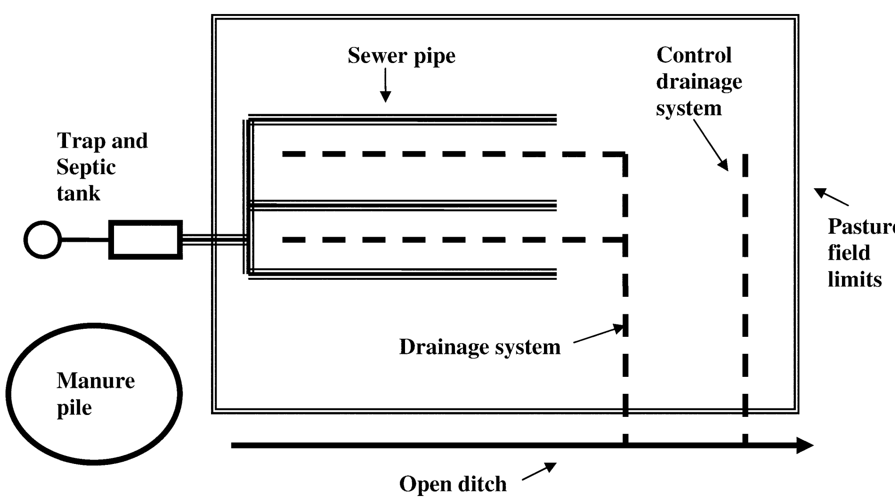

Figure 3 Schematic of sewer pipe and subsurface drainage in the seepage field of Farm MH-1.

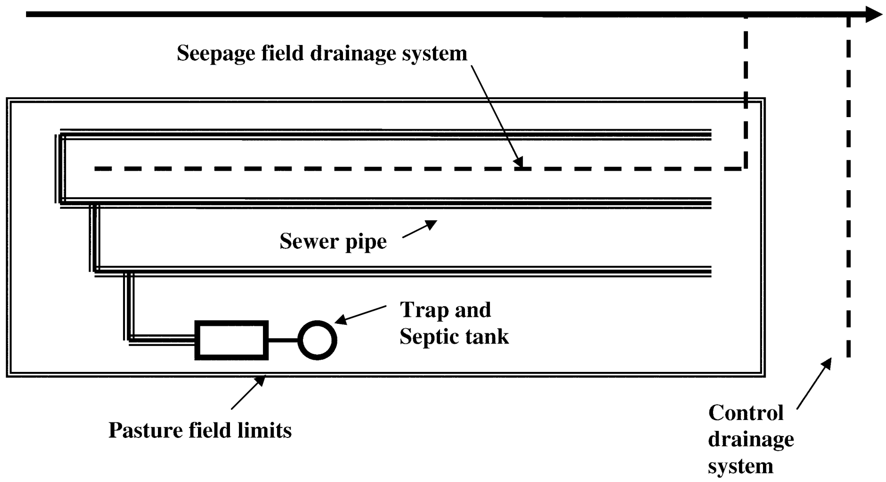

Figure 4 Schematic of sewer pipe and subsurface drainage in the seepage field of Farm MH-2.

was expressed as the litres of wastewater generated per number of cows in the herd, per day for each month of the study. Samples of wastewater were also collected from the sediment and milk fat trap on a monthly basis, except during the cold winter months. Because sediments tended to accumulate at bottom of the trap, while milk fat solidified at the top, these were sampled and analyzed separately.

Water samples were collected periodically from the outlet of the subsurface system draining the seepage field, as well as the outlet of a control drainage system. On Farm MH-1, the control drainage system was a single subsurface drain installed further down the pasture field; because of its limited length, it produced less drainage water than the subsurface drainage system of the seepage field. On Farm MH-2, the control drainage system was in a cropped field adjacent to the pasture where the seepage field was built. Both seepage fields were exposed to outside sources of contamination. On Farm MH-1, solid manure was stock-piled directly on the ground and its contaminated runoff seeped into the upper corner of the area occupied by the seepage field. On Farm MH-2, the control field received no manure while the pasture covering the seepage field was occupied by dry cows and heifers, and thus received manure continuously during six months of the year.

Water samples, sediments and milk fat were analysed using standard methods (APHA, 1998). Total solids (TS) were determined gravimetrically after drying for 24 h at 103°C. Suspended and dissolved solids (SS and DS) were analyzed by filtering through a 0.45 μm filter and drying for 2 and 24 h at 103°C. The pH was determined using a pH probe connected to an Orion meter, while EC was measured with a YSI 30 S-C-T conductivity meter (Yellowspring, Ohio). After digesting all samples at 500°C using 18 M sulphuric acid and 50% hydrogen peroxide, the total N (TN) concentration was determined using an ammonia sensitive probe connected to an Orion pH meter, and total P and total K (TP and TK) were determined colorimetrically (Hach Corporation, Loveland, Ohio). Conducted only on the milk fat collected in the trap, chemical oxygen demand (COD) was determined colorimetrically after oxidization with potassium chromate at 140°C (Hach Corporation, Loveland, Ohio). Bacterial populations, namely total coliforms (TC), fecal coliforms (FC) and fecal streptococci (FS) were determined using the micro-filtration method and expressed as the number of colony-forming units per ml of water (APHA, 1998).

The nutrient load in milk house wastewater entering the seepage field was the volume of milk house wastewater generated per month multiplied by the nutrient concentration in each monthly wastewater sample. The monthly nutrient loads were summed to provide an annual nutrient load. The nutrient load excluded the nutrients contained in milk fat and sediments, since these components of wastewater were mostly removed in the trap before the septic tank.

2.3 Soil sampling and analysis

Soil samples were collected from the seepage field of Farm MH-1 and Farm MH-2 at the time that sewage and subsurface drainage pipes were installed. These samples were taken from locations along a transect in the seepage field, to characterize soil properties at the top of the slope, near the septic tank (Top), in the middle of the seepage field (Middle), and at the bottom of the slope, near the drain outlet (Bottom). At each location, soil was collected from depths of 0–20 cm, 20–40 cm and 40–60 cm at sampling positions 0, 0.5, 1 and 3 m from the subsurface drainage pipe. In May 2004 and September 2004, the seepage field of Farm MH-1 and Farm MH-2 was again sampled. At each of the three locations, a soil sample (composite of five cores taken with a 4.5 cm diameter auger) was collected from depths of 0–20 cm, 20–40 cm and 40–60 cm at sampling positions 0, 0.5, 1 and 3 m from the subsurface drainage system. In September 2004, we also collected soil from the extreme end of the pasture, beyond the seepage field, to serve as a Control.

Soil samples were sieved (<2 mm) and oven-dried (60°C for 48 h) prior to analysis. Soil pH and electrical conductivity were determined in 1:2 soils: water slurries (Hendershot, Lalonde, & Duquette, 1993) using an Accumet AR10 pH meter and a CDM83 microcell conductivity meter. The plant-available NH_4-N and NO_3-N concentrations were determined in 2 M KCl extracts (1:5 soil:solution) using the cadmium reduction–diazotization and salicylate methods (Maynard & Kalra, 1993). Extracts were analysed on a Lachat Quik-Chem AE flow injection autoanalyzer (Lachat Instruments, Milwaukee, WI, USA). Mineral N was the sum of the NH_4-N plus NO_3-N in each sample. Plant-available nutrients (P, K, Ca and Mg) were extracted with Mehlich III solution (1:10 soil:solution) for after shaking for 5 min at 130 rpm (Tran & Simard, 1993). The Mehlich-3 P concentration was determined using the ammonium molybdate-ascorbic acid method (Murphy & Riley, 1962) on a Lachat Quik-Chem AE flow injection autoanalyzer (Lachat Instruments, Milwaukee, WI, USA), while K, Ca and Mg concentrations were determined by atomic absorption spectrometry.

2.4 Statistical analysis

Prior to analysis, the data were tested for normality using the Kolmogorov–Smirnov test and were $\log_e$- or square root-transformed when required to adjust for normality and stabilize variance. The data from each farm were analyzed by analysis of variance (ANOVA) using the PROC GLM procedure of SAS statistical software package (SAS System 9.1, SAS Institute Inc., Cary, NC). Soil parameters were affected significantly ($P<0.05$) by the following factors: sampling date (July 2003, May 2004, September 2004), sampling location (Top, Middle and Bottom of slope) and soil depth (0–20, 20–40 and 40–60 cm). No soil parameter was affected by the sampling position (0, 0.5, 1 and 3 m from the subsurface drainage pipe), so these data were pooled to increase the number of replicate measurements.

Soil samples collected in July 2003, at the time the seepage field was constructed, were considered to represent initial soil characteristics, and served as a control (Con2003). Soils collected from the seepage field in May 2004 and September 2004 represented the soil conditions after exposed to milk house wastewater (WW), while soil collected from the extreme end of the pasture, beyond the seepage field, in September 2004 also served as a control (Con2004). The effect of milk house wastewater on soil parameters within each soil depth was determined by one-way ANOVA and contrast analysis between the WW-treated soils and Control soils (Con2003, Con2004) at the 95% confidence level (Steel, Torrie, & Dickey, 1997).

3 Results and Discussion

3.1 Milk house wastewater characteristics and nutrient loads

Milk house wastewater characteristics were assessed once a month on Farms MH-1 and MH-2 and compiled into average values (Tables II and III). During the 30 months of monitoring, the average total solids were relatively low, at less than 0.5%. The milk house wastewater pH on Farm MH-1 was between 5.9 and 6.5 while that on Farm MH-2 ranged from 7.6 to 8.1, likely because of the water softener used on this farm. On Farm MH-1, the nutrient loads ranged from 12 to 268 mg TN l^{-1}, with 72 to 155 mg TP l^{-1} and 42 to 350 mg TK l^{-1}. Similar nutrient loads were calculated for Farm MH-2, ranging from 12 to 118 mg TN l^{-1}, 42 to 213 mg TP l^{-1} and 57 to 443 mg TK l^{-1}.

Farm MH-1 produced 13.1 l of milk house wastewater per cow per day, while Farm MH-2

Table II Average milk house wastewater characteristics for Farm MH-1

Parameter	2003			2004			2005		
	Ww	Sed	Fat[a]	Ww	Sed	Fat[a]	Ww	Sed	Fat[a]
TS, %	0.33	ND	19.7	0.30	ND	20.6	0.46	ND	12.8
SS, %	0.10	ND	NA	0.12	ND	NA	0.10	ND	NA
DS, %	0.23	ND	NA	0.18	ND	NA	0.36	ND	NA
pH	6.4	ND	NA	5.9	ND	NA	6.5	ND	NA
TN, mg l^{-1}	106	ND	5463	124	ND	1062	64	ND	598
TP, mg l^{-1}	71	ND	101	94	ND	130	107	ND	93
TK, mg l^{-1}	213	ND	187	217	ND	219	145	ND	341
COD[b], g kg^{-1}	NA	ND	460	NA	ND	611	NA	ND	644
TC, CFU ml^{-1}	NA	ND	NA	NA	ND	NA	1400	ND	NA
FC, CFU ml^{-1}	NA	ND	NA	NA	ND	NA	17000	ND	NA
FS, CFU ml^{-1}	NA	ND	NA	NA	ND	NA	3200	ND	NA

Ww Wastewater, *Sed* sediments, *Fat* milk fat, *TS* total solids, *SS* suspended solids, *DS* dissolved solids, *TN* total N, *TP* total P, *TK* total K, *COD* chemical oxygen demand, *TC* total coliforms, *FC* fecal coliforms, *FS* fecal streptococci, *CFU* counts by filtration unit, *NA* not analyzed, *ND* not detected

[a] TN, TP and TK are expressed as g kg^{-1} dry matter

[b] COD was conducted only on the milk fat, because of the expected low value of the wastewaters and sediments

produced 12.5 l cow^{-1} d^{-1} (Table IV). These values are consistent with wastewater production of 15 to 20 l cow^{-1} d^{-1} reported by Urgel Delisle et Ass. Inc. (1994). The annual nutrient load generated by the milk house wastewaters entering the seepage field was greater on Farm MH-1 than that for Farm MH-2, likely because the producer discharged wasted milk into the septic system. On Farm MH-2, this wasted milk was sent to the manure storage facility to prevent overloading of the septic system. The phosphorus and potassium loads, of 40 to 60 kg TP ha^{-1} y^{-1} and 75 to 85 kg TK ha^{-1} y^{-1}, corresponded to the nutrient uptake of a high yielding forage crop, such as corn silage or alfalfa (10 dry tons ha^{-1} y^{-1}). The nitrogen load of 50 to 65 kg TN ha^{-1} y^{-1} was about half of the nitrogen required by a corn silage crop, but greater than the nitrogen recommendation for an alfalfa crop (CRAAQ, 2003).

Table III Average milk house wastewater characteristics for Farm MH-2

Parameter	2003			2004			2005		
	Ww	Sed[a]	Fat	Ww	Sed	Fat	Ww	Sed[a]	Fat
TS, %	0.29	NA	ND	0.27	NA	ND	0.30	NA	ND
SS, %	0.07	NA	ND	0.03	NA	ND	0.04	NA	ND
DS, %	0.22	NA	ND	0.24	NA	ND	0.26	NA	ND
pH	7.6	NA	ND	8.1	NA	ND	7.9	NA	ND
TN, mg l^{-1}	46	NA	ND	47	1943	ND	73	1448	ND
TP, mg l^{-1}	97	NA	ND	82	1227	ND	77	504	ND
TK, mg l^{-1}	350	NA	ND	128	1366	ND	67	395	ND
TC, CFU ml^{-1}	NA	NA	ND	NA	NA	ND	2100	NA	ND
FC, CFU ml^{-1}	NA	NA	ND	NA	NA	ND	5000	NA	ND
FS, CFU ml^{-1}	NA	NA	ND	NA	NA	ND	8×10^{4}	NA	ND

Ww Wastewater, *Sed* sediments, *Fat* milk fat, *TS* total solids, *SS* suspended solids, *DS* dissolved solids, *TN* total N, *TP* total P, *TK* total K, *TC* total coliforms, *FC* fecal coliforms, *FS* fecal streptococci, *CFU* counts by filtration unit, *NA* not analyzed, *ND* not detected

[a] TN, TP and TK expressed as g kg^{-1} dry matter

Table IV Annual nutrient load in milk house wastewater entering the seepage fields of two dairy farms, estimated from the monthly nutrient load and volume of milk house wastewater produced on dairy farms

Nutrient load	Farm MH-1			Farm MH-2		
	TN	TP	TK	TN	TP	TK
Average[a], mg l^{-1}	118 (51)	109 (90)	142 (129)	117 (70)	98 (32)	210 (135)
Yearly, kg cow^{-1}	0.57	0.52	0.68	0.53	0.45	0.96
Total, kg ha^{-1} y^{-1}	65	60	75	50	40	85

Farm MH-1 and MH-2 produced 13.1 and 12.5 l cow^{-1} d^{-1} of milk house wastewater, respectively

TN Total N, *TP* total P, *TK* total K

[a] The value in parenthesis is the standard deviation (n=26). The loading rates do not consider the impact of sediments and milk fat, which normally would be removed from the trap and disposed with solid manure

3.2 Soil parameters in the seepage field

Analysis of soils at the time of seepage field construction (Con2003) provided a measure of the heterogeneity in soil parameters that occurred along the transect, from the top to the bottom of the slope, and within the soil horizon at each sampling location (Tables V, VI, VII, VIII, IX, and X). The seepage field of Farm MH-1 received, on average, 16 mm of wastewater y^{-1}, while Farm MH-2 received 19 mm y^{-1} of water in its seepage field.

Soil parameters were measured twice during the year that milk house wastewater began entering the seepage field, and were compared to the initial soil conditions and the soil characteristics of an adjacent control field (Con2004) that did not receive milk house wastewater for the duration of the study (Table V, VI, VII, VIII, IX, and X). We consider that soil characteristics changed when (1) the parameter was significantly ($P<0.05$, contrast analysis) different for both Con2003 vs. wastewater (WW)-treated soil and Con2004 vs. WW-treated soil comparisons and (2) the trend was consistent (e.g., the WW-treated soils had lower values, compared to both controls). If the milk house wastewaters did have an effect on soil characteristics, we expected the effects to be noticeable first in the 40 to 60 cm layer, corresponding to the depth of installation of the sewer pipes. Changes in surface soil characteristics are more likely to be due to the presence of cattle in the pasture overlying the seepage field, or other agricultural practices (cultivation, arable crop production). On both farms, the Con2004 site was located at the extreme end of the pasture, where cattle may have been less likely to roam.

Table V Changes in soil properties (0–20 cm depth) along a transect (top to bottom of slope) in the seepage field on Farm MH-1

Parameter	Control		Top		Middle		Bottom		Contrast analysis	
	July 2003	Sep 2004	May 2004	Sep 2004	May 2004	Sep 2004	May 2004	Sep 2004	Con2003 vs. WW	Con2004 vs. WW
pH	6.7	6.1	6.1	6.1	6.6	6.7	6.3	6.4	P=0.0001	P=0.0143
EC, dS m^{-1}	0.84	1.9	1.6	1.4	2.2	2.4	1.8	2.1	P=0.0006	NS
NH_4-N, mg kg^{-1}	0.83	20	5.2	22	7.6	15	4.9	24	P=0.0001	P=0.0630
NO_3-N, mg kg^{-1}	15	21	13	10	22	32	27	14	NS	NS
P, mg kg^{-1}	49	52	55	53	25	40	41	55	NS	NS
K, mg kg^{-1}	161	180	75	109	83	106	89	75	P=0.0071	P=0.0437
Ca, mg kg^{-1}	1439	1365	1208	1250	1915	2285	1480	1403	P=0.0142	P=0.0328
Mg, mg kg^{-1}	306	231	299	200	408	495	415	253	P=0.0398	P=0.0011

EC Electrical conductivity, *Con2003* control soils collected in July 2003, *Con2004* control soils collected in September 2004, *WW* soils from the seepage field receiving milk house wastewater; *NS* not significant – $P>0.1$

Table VI Changes in soil properties (20–40 cm depth) along a transect (top to bottom of slope) in the seepage field on Farm MH-1

Parameter	Control		Top		Middle		Bottom		Contrast analysis	
	July 2003	Sep 2004	May 2004	Sep 2004	May 2004	Sep 2004	May 2004	Sep 2004	Con2003 vs. WW	Con2004 vs. WW
pH	6.8	6.2	6.2	6.2	6.7	6.7	6.5	6.4	P=0.0003	P=0.0500
EC, dS m^{-1}	0.49	0.81	1.4	1.2	1.6	1.1	1.5	0.67	P=0.0001	P=0.0425
NH_4-N, mg kg^{-1}	0.65	14	4.0	14	5.4	3.9	4.8	9.3	P=0.0001	P=0.0009
NO_3-N, mg kg^{-1}	8.9	5.2	8.9	9.4	14	6.5	11	3.1	NS	P=0.0448
P, mg kg^{-1}	12	31	48	42	15	7.1	27	7.9	P=0.0018	NS
K, mg kg^{-1}	87	96	90	141	97	96	89	79	NS	NS
Ca, mg kg^{-1}	1195	745	1338	1033	1745	2127	1517	1255	P=0.0013	P=0.0001
Mg, mg kg^{-1}	340	203	270	218	393	631	434	435	P=0.0615	P=0.0005

EC Electrical conductivity, *Con2003* control soils collected in July 2003, *Con2004* control soils collected in September 2004, *WW* soils from the seepage field receiving milk house wastewater, *NS* not significant – P>0.1

The results from Farm MH-1 and Farm MH-2 were presented separately because the magnitude of change in soil parameters was farm-specific, due to the unique topography and soil characteristics offered by each farm. Cultivating the pasture and seeding it with a cereal crop on Farm MH-1 likely had an impact on the soil nutrient values, especially within the top 0–20 cm layer.

On Farm MH-1, we observed greater plant-available Ca concentrations in all soil layers, to a depth of 60 cm, and greater plant-available Mg concentrations in the 0–20 cm and 20–40 cm depths, in the seepage field than in the controls (Tables V, VI, and VII). These cations were probably introduced with the milk house wastewater. No K accumulation was noted, and the plant-available K concentration in the 0–20 cm layer was lower in the seepage field than the control, which may be due to greater K removal by the crop in this subirrigated system than in the non-irrigated control field. On Farm MH-2, there were also some evidence of Ca and Mg accumulation due to the milk house wastewater, since only the 40–60 cm layer of the seepage field contained more Ca than the controls (Tables VIII, IX, and X). However, the K concentration

Table VII Changes in soil properties (40–60 cm depth) along a transect (top to bottom of slope) in the seepage field on Farm MH-1

Parameter	Control		Top		Middle		Bottom		Contrast analysis	
	July 2003	Sep 2004	May 2004	Sep 2004	May 2004	Sep 2004	May 2004	Sep 2004	Con2003 vs. WW	Con2004 vs. WW
pH	6.8	6.4	6.1	6.2	6.7	6.8	6.5	6.4	P=0.0001	NS
EC, dS m^{-1}	0.42	0.62	1.7	0.74	1.9	0.87	1.6	0.69	P=0.0001	P=0.0001
NH_4-N, mg kg^{-1}	0.67	7.4	5.6	4.7	6.9	3.3	4.6	14	P=0.0001	NS
NO_3-N, mg kg^{-1}	7.9	2.2	12	2.3	16	2.8	10	2.0	NS	P=0.0009
P, mg kg^{-1}	6.9	10	30	17	26	3.5	19	5.2	P=0.0010	NS
K, mg kg^{-1}	67	99	173	116	90	117	96	86	P=0.0084	NS
Ca, mg kg^{-1}	1278	985	1155	1200	1940	1748	1470	1275	P=0.0040	P=0.0001
Mg, mg kg^{-1}	448	345	254	322	382	555	481	485	NS	P=0.0777

EC Electrical conductivity, *Con2003* control soils collected in July 2003, *Con2004* control soils collected in September 2004, *WW* soils from the seepage field receiving milk house wastewater, *NS* not significant – P>0.1

Table VIII Changes in soil properties (0–20 cm depth) along a transect (top to bottom of slope) in the seepage field on Farm MH-2

Parameter	Control		Top		Middle		Bottom		Contrast analysis	
	July 2003	Sep 2004	May 2004	Sep 2004	May 2004	Sep 2004	May 2004	Sep 2004	Con2003 vs. WW	Con2004 vs. WW
pH	7.4	7.3	7.6	7.7	7.4	7.3	7.3	7.1	NS	NS
EC, dS m^{-1}	2.8	3.1	3.2	3.6	2.4	3.7	1.8	2.1	NS	NS
NH_4-N, mg kg^{-1}	2.0	16	4.6	8.5	7.8	13	6.8	14	P=0.0001	P=0.0001
NO_3-N, mg kg^{-1}	25	32	9.0	39	17	19	8.8	10	P=0.0300	P=0.0127
P, mg kg^{-1}	183	148	250	258	220	284	106	116	NS	NS
K, mg kg^{-1}	274	390	500	612	617	758	470	720	P=0.0011	P=0.0027
Ca, mg kg^{-1}	2789	3783	2902	4012	3575	3555	3118	2720	P=0.0028	P=0.0952
Mg, mg kg^{-1}	594	711	336	522	479	573	601	546	P=0.0119	P=0.0005

EC Electrical conductivity, *Con2003* control soils collected in July 2003, *Con2004* control soils collected in September 2004, *WW* soils from the seepage field receiving milk house wastewater, *NS* not significant – P>0.1

was greater throughout the soil profile of the seepage field than in control soils (Tables VIII, IX, and X).

The accumulation of K, Mg and Ca in these soils is unlikely to have a negative environmental impact, since these cations tend to become fixed in soils and when leached do not pose any known risk for water quality. Yet, Wang, Magesan, and Bolan (2004) noted that applying dairy effluents with high K concentrations to pasture can lead to nutrient imbalances in forages when soils test low for plant-available Ca and Mg. Routine soil and plant tissue testing is necessary to detect such imbalances, which can be corrected by applying supplemental fertilizers.

Increasing soil salinity following surface and subsurface irrigation has been documented in all parts of the world, due to the differences in the transport of salts and water in the soil profile (Rengasamy, 2006). The seepage fields on Farm MH-1 and Farm MH-2 were sized to permit nutrient loading at a rate that did not greatly exceed crop nutrient requirements. This strategy resulted in very little salt accumulation on both farms. Although salt accumulation occurred in

Table IX Changes in soil properties (20–40 cm depth) along a transect (top to bottom of slope) in the seepage field on Farm MH-2

Parameter	Control		Top		Middle		Bottom		Contrast analysis	
	July 2003	Sep 2004	May 2004	Sep 2004	May 2004	Sep 2004	May 2004	Sep 2004	Con2003 vs. WW	Con2004 vs. WW
pH	7.7	7.4	7.8	7.6	7.5	7.4	7.3	7.2	P=0.0007	NS
EC, dS m^{-1}	2.9	2.1	2.5	3.2	1.9	3.2	1.5	2.0	NS	NS
NH_4-N, mg kg^{-1}	0.92	8.2	5.1	8.5	6.7	7.4	6.2	8.2	P=0.0001	NS
NO_3-N, mg kg^{-1}	8.5	24	8.7	29	11	20	6.7	8.4	NS	P=0.0907
P, mg kg^{-1}	51	35	127	134	126	155	60	57	P=0.0022	P=0.0157
K, mg kg^{-1}	329	173	445	338	518	582	379	541	P=0.0079	P=0.0001
Ca, mg kg^{-1}	2144	2255	2382	2885	3188	2927	2840	2070	P=0.0092	NS
Mg, mg kg^{-1}	486	548	414	396	534	523	523	518	NS	NS

EC Electrical conductivity, *Con2003* control soils collected in July 2003, *Con2004* control soils collected in September 2004, *WW* soils from the seepage field receiving milk house wastewater, *NS* not significant – P>0.1

Table X Changes in soil properties (40–60 cm depth) along a transect (top to bottom of slope) in the seepage field on Farm MH-2

Parameter	Control		Top		Middle		Bottom		Contrast analysis	
	July 2003	Sep 2004	May 2004	Sep 2004	May 2004	Sep 2004	May 2004	Sep 2004	Con2003 vs. WW	Con2004 vs. WW
pH	7.9	7.5	7.9	7.6	7.6	7.4	7.3	7.2	P=0.0002	NS
EC, dS m^{-1}	2.8	1.6	1.5	2.3	1.2	3.1	1.4	2.2	NS	NS
NH_4-N, mg kg^{-1}	0.98	7.5	4.9	3.3	4.2	6.7	4.7	6.6	P=0.0001	P=0.0375
NO_3-N, mg kg^{-1}	5.4	15	6.5	13	6.2	17	8.0	6.9	NS	NS
P, mg kg^{-1}	11	22	50	51	54	79	32	28	P=0.0001	P=0.0351
K, mg kg^{-1}	241	114	710	338	686	503	557	561	P=0.0001	P=0.0001
Ca, mg kg^{-1}	1624	1698	2165	2015	2545	2625	2835	2110	P=0.0006	P=0.0501
Mg, mg kg^{-1}	475	441	334	342	480	591	590	519	NS	NS

EC Electrical conductivity, *Con2003* control soils collected in July 2003, *Con2004* control soils collected in September 2004, *WW* soils from the seepage field receiving milk house wastewater, *NS* not significant – P>0.1

the 20–60 cm soil depth on Farm MH-1, the EC level on Farm MH-1 did not exceed 2.0 dS m^{-1} (Tables V, VI, and VII). No measurable salt accumulation was observed on Farm MH-2, where the highest EC value was 3.7 dS m^{-1} (Tables VIII, IX, and X). These values are considered to be low, as most crops can readily tolerate soil solutions with salinity levels of 4.0 dS m^{-1} (Alberta Agriculture, 2001).

Ammonium (NH_4-N) and nitrate (NO_3-N) were both present in the seepage fields on both dairy farms (Tables V, VI, VII, VIII, IX, and X). The majority of plant-available N in milk house wastewater is NH_4-N, and the presence of a large soil NO_3-N pool suggests that nitrification occurred in the seepage field (Havlin, Beaton, Tisdale, & Nelson, 1999), leading us to infer that the quantities of wastewater entering the seepage field did not induce anaerobic conditions. Excessive soil NO_3-N can contribute to environmental pollution if it is not efficiently captured by plant roots. Regular monitoring of the NO_3-N levels in drainage water would be needed to verify the efficiency of N recycling in the soil–plant system of the seepage field.

The accumulation of plant-available P following wastewater application is a concern due to the potential for eutrophication when P from agricultural land enters surface waters. On Farm MH-1, the P concentration in the soil profile did not change when milk house wastewater entered the seepage field, but the initial soil P concentration in the 0–20 cm depth (49 mg Mehlich-3 P kg^{-1} in July 2003) was lower than the critical level of 66 mg Mehlich-3 P kg^{-1} in topsoil established by the Ministère de l'Environnement du Québec (1999). In contrast, the soil P concentration in topsoil of Farm MH-2 was initially more than two times the critical level (Tables VIII, IX, and X). Although the soil P concentration did not change in the 0–20 cm depth on Farm MH-2, the soil P concentration in the 20–40 cm and 40–60 cm depths increased significantly (P<0.05) after milk house wastewater began entering the seepage field (Tables VIII, IX, and X). Because this large increase in soil P exceeds the P load applied by the wastewaters, these results suggest that P may become more available in some soils when milk house wastewater is released through a seepage field. The mechanism responsible for this observation is not known, but anoxic conditions induced by periodic flooding can cause Fe^{+3} to be reduced to Fe^{+2}, releasing P from Fe–P compounds and increasing the extractable soil P concentration (Havlin et al., 1999). Regular monitoring is required to ensure that subsurface P accumulation does not cause water pollution.

Our results provide some insight into the short-term changes in soil pH, EC and plant-available nutrient concentrations that may occur when milk house wastewater is disposed through subsurface drainage into a seepage field. Our assumption that the seepage field was large enough to absorb the nutrients from milk house wastewater could be confirmed by determining the cation and anion adsorption capacity of the soils on each farm, although routine monitoring of drain water quality is also necessary because nutrients can bypass adsorption sites and be transported from soils via preferential flow (i.e., soil macropores).

3.3 Drainage water quality in the seepage field

There was no difference ($P>0.05$, pairwise t-test) in the analyses of water collected from subsurface drains in the seepage field and a nearby control field on both farms (Table XI). However, the drain water contained a higher TN concentration than the Canadian drinking water standard, which is 10 mg NO_3-N l^{-1} (Health and Welfare Canada, 1996). The TP concentration in the drainage water exceeded the Quebec provincial surface water quality standard of 0.03 mg TP l^{-1} (Ministère de l'Environnement du Québec, 2000). This suggests that water emanating from these farms has the potential to pollute ground and surface water, whether it comes from the seepage field or adjacent agricultural land.

On Farm MH-1, the drainage water from the control system tended to have more total N than that from the seepage field, despite the fact that the seepage field was likely contaminated by manure runoff, because water from the control system could only be collected when very wet conditions led to flushing of the drain (Table XI). There was no difference in any other drainage water parameter between the seepage field and control system on Farm MH-1. On Farm MH-2, both the control and seepage field drainage waters could be collected at the same time. Drainage water from the seepage field tended to have a slightly higher nitrogen concentration than the control system, which may be a result of pasturing cows over the area occupied by the seepage field. However, there was no difference in drainage water quality in the seepage field and control system on Farm MH-2 (Table XI).

These results confirm our observation that the soil effectively absorbed the nutrients added by the milk house wastewaters. Monitoring of the seepage fields over a longer period of time is likely necessary to measure the true impact of the modified septic system on soil nutrient loading and drainage water quality.

4 Conclusions

A modified septic system was designed to allow small dairy farms to treat their milk house wastewaters economically and efficiently. The modified system consisted of a sediment and milk fat trap installed before the septic tank and an enlarged seepage field installed below a cropped area where treated wastewater was discharged. The size of the seepage field (0.45 ha) was based on the annual nutrient uptake by the crop. The two farms included in this study produced 12.5 and 13.1 l of milk house wastewater cow^{-1} d^{-1}, which led to the application of 50 to 65 kg TN ha^{-1} y^{-1}, 40 to 60 kg TP ha^{-1} y^{-1} and 75 to 85 kg TK ha^{-1} y^{-1}. Disposing of milk house wastewater in the seepage field increased the concentration of some plant-available nutrients, although the magnitude of change was farm-specific, due to the unique topography, soil characteristics and agricultural practices on each farm. Plant-available Ca concentrations were elevated at the depth of sewage pipes (40–60 cm),

Table XI Quality of the drainage waters collected from the outlet of the seepage field and a nearby field (control system)

Parameter	Farm MH-1		Farm MH-2	
	Seepage field[a]	Control system	Seepage field	Control system
pH	6.8	6.9	6.8	7.0
	(0.5)	(0.4)	(0.5)	(0.5)
TN, mg l^{-1}	10.0	21.9	13.4	8.6
	(8.8)	(11.3)	(10.0)	(3.7)
TP, mg l^{-1}	0.4	0.4	0.7	0.6
	(0.7)	(0.5)	(0.8)	(0.9)
TK, mg l^{-1}	171	127	28.9	24.8
	(129)	(134)	(20.4)	(35.6)
EC, dS m^{-1}	0.6	0.4	0.8	0.6
	(0.3)	(0.05)	(0.3)	(0.2)
Sample number	25	9	33	33

TN Total N, *TP* total P, *TK* total K, *EC* electrical conductivity

[a] The value in parenthesis is the standard deviation of the mean

likely due to the Ca contained in milk house wastewater, and plant-available Mg, K and NH_4-N concentrations were also greater in some soil depths when milk house wastewater was applied. Soil salinity was low (<4 dS m^{-1}) and should not affect crop performance on these farms. We also observed a significant increase in the plant-available P concentration within the soil profile (20–60 cm depth) of one farm, but drainage water quality was similar in the seepage field as an adjacent cropped field that did not receive milk house wastewater. These results indicate that, in the short-term, the seepage field was sufficiently large to adsorb and treat the nutrients contained in milk house wastewater. Regular monitoring of soils and drain water quality is needed to verify that the seepage field continues to function correctly for environmental protection.

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