Agriculture, Ecosystems and Environment 264 (2018) 85–93

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Silage storage runoff characterization: Annual nutrient loading rate and first flush analysis of bunker silos

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ARTICLE INFO

Keywords:
Bunker silo
Cattle
Dairy
First flush
Nutrient management
Runoff
Silage
Silage effluent
Silage leachate
Silage pile

ABSTRACT

Bunker silos produce a runoff that is a source of nutrient loss and a threat to surface water quality. Little information is available on the water quality of stormwater produced from bunker silos. This research evaluated the runoff characteristics from six horizontal bunker facilities at dairy farms to determine runoff water quality and nutrient loading throughout a storm and annual nutrient losses. On average, at 50% of the cumulative runoff volume the difference between cumulative nutrient load and volume did not exceed 20%, which is a threshold required for a first flush scenario (cumulative loads of P and N were 1.5 to 4.5% and −2.8 to 4.0% greater than cumulative volume, respectively). During the storage of silage in horizontal bunker silos an estimated 0.3 to 1.8% of ensiled P and 0.4 to 1.7% of ensiled N was lost annually with silage runoff. Assessment of a theoretical dairy farm in WI has a calculated runoff loss from horizontal feed storage of 30% and 55% of the total farmstead N and P runoff losses, respectively. Nitrogen (N) and phosphorus (P) loading from bunker silos were relatively consistent throughout a storm with no evidence of a first flush scenario. Annual variability in low flow N and P concentrations were impacted by the production of silage leachate, and bunkers with subsurface collection reduced the nutrient concentrations in overflow runoff. Dairy bunkers provide an opportunity to decrease nutrient loading, through management of a small land base, as compared to other farmstead runoff areas. Reducing the amount of silage runoff lost from dairy farms has strong potential for N and P conservation.

1. Introduction

Dairy and cattle producers ensile forage to preserve feed for use throughout the year. In 2010, 100 million tons of hay silage and 107 million tons of corn silage was produced in the United States (USDA-NASS, 2012). Storage of silage is known to generate wastewater in the form of leachate and runoff. Silage leachate is corrosive and has elevated nutrient concentrations (Cropper and DuPoldt, 1995; Cumby et al., 1999; Faulkner et al., 2010) that can contaminate ground and surface water. Silage leachate can be acidic with a pH from 3.5 to 5.5, contain phosphorus at concentrations reported of 300 to 600 mg L^{-1}, organic nitrogen of 800 to 3700 mg L^{-1}, and five-day biological oxygen demand (BOD_5) of 12,000 to 90,000 mg L^{-1} (McDonald et al., 1991).

Silage runoff is produced during a precipitation or snowmelt event where runoff comes into contact with silage piles, litter on the pad, and base flows of silage leachate. The concept of silage runoff was first introduced by Wright et al. (2004) as it was speculated that the total amount of effluent from a bunker silo was dependent on the amount of rainfall and that precipitation creates runoff from bunkers diluting the silage juice. Although, other dairy farm area runoff has been extensively studied such as feed lot runoff (Koelsch et al., 2006) the nutrient losses from dairy bunkers has yet to be thoroughly investigated. The recent shift to larger average dairy herd sizes in the U.S., averaging 120 cows per farm in 2006 (Macdonald et al., 2007), has increased the adoption of horizontal bunkers silos/piles. Horizontal bunkers allow faster silage loading and unloading rates to meet the needs of larger facilities but issues have emerged on the proper management of silage effluent. Silage runoff is a global concern as an estimated 15% (and growing) of the dairy cows globally are on farms with > 100 cows including farms in the U.S., U.K., Argentina, Uruguay, South Africa, Oceania, Saudi Arabia, Czech Republic, and parts of Europe (Mikesell, 2016).

The limited existing research on silage runoff has measured more dilute contaminate concentrations than leachate, but concentrations that still pose a risk to surface and groundwater (Clarke and Stone, 2004; Faulkner et al., 2010; Wright et al., 2004). Silage effluent losses from leachate alone are estimated to be as high as 15% of the nutrients harvested and as much as 3.2 kg of P per cow per year (Wright et al., 2004). Concentrated flows from a bunker into a watershed, could result

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https://doi.org/10.1016/j.agee.2018.05.015
Received 12 December 2017; Received in revised form 7 May 2018; Accepted 16 May 2018

in environmental contamination of ground and surface water. Nutrient concentrations in silage runoff are variable, likely due to the concentration of silage leachate, storm size, season, and bunker conditions (Wright et al., 2004). A paucity of information exists on the influence of these variables on silage runoff production and impact of seasonality on silage runoff production as silage runoff was only previously intensively monitored from three bunkers in the summer and fall (Wright et al., 2004).

At large permitted dairy facilities (> 1000 animal units) following the National Pollutant Discharge Elimination system in the U.S., silage effluent management is historically designed to separate low strength and high strength waste (Clarke and Stone, 2004). These collection systems are intended to capture a first flush, a phenomenon where a majority of the contaminant loading occurs within a storm's initial runoff volume, in order to collect the high strength waste. The captured first flush is commonly sent to the manure storage where it is then applied to fields according to a nutrient management plan. First flush of nutrients occurs from impervious areas in urban settings (Lee et al., 2002) and therefore impervious silage bunker collection systems have been designed to collect the initial wastewater produced from a runoff event with the intent of collecting the highest strength waste, although this phenomena has yet to be verified in this setting. Capturing high concentrated wastewater minimizes the volume requiring storage and subsequent land application (or alternative treatment prior to discharge). The subsequent lower strength storm water (silage runoff) is then usually routed to a vegetated treatment area or other low-cost treatment system. When vegetated treatment systems are managed correctly these systems can reduce downstream pollution (Wright et al., 2004), mainly through infiltration. However, over-application of nutrients to these filter-strips with silage runoff can result in surface and groundwater contamination, highlighting the need for detailed characterization (Holly and Larson, 2016). This research evaluated the quantity and quality of silage runoff from six dairy silage bunkers in Wisconsin, over individual precipitation events and multiple years, to guide system design and management in an attempt to reduce impacts to water quality.

2. Methods & materials

Runoff from six dairy silage bunker sites A, B, C, D, E, and F (Table 1), all located in Wisconsin, was collected and analyzed to determine water quality characteristics. Three sites (A, B, and C) were intensively monitored, with frequent sampling throughout each storm. Sites A, B, and C were monitored over the Fall, Summer, and Spring of 2011 and 2012 for a total of 9, 14, and 11 storms, respectively. Sites A is located on the agricultural research station for the University of Wisconsin-Madison in Arlington, WI, site B is the U.S. Dairy Forage Research Center Farm of the USDA-ARS, located in Prairie Du Sac, WI, and site C is privately owned, located in south-central Wisconsin. An additional three sites (D, E, and F) were composite sampled to determine annual loading. Sites D, E, and F were monitored year round over 2012 to 2014 for a total of 210, 120, and 75 rain events, respectively. The intensively sampled sites were within Dane and Sauk counties and the composite measured sites were located in St. Croix, Marinette, and Brown counties (Figure B.1 found in the appendix). Rainfall was recorded using tipping bucket rain gauges (Teledyne Technologies, Inc., 674 Rain Gauge) at all sites. Refrigerated runoff samples for all six sites were collected within 24 h of a rainfall event, stored on ice, subsampled, and preserved. Chemical analysis was completed on filtered and unfiltered subsamples included pH, total solids (TS), biological oxygen demand BOD_5, chemical oxygen demand (COD), total phosphorus (TP), soluble reactive phosphorus (SRP), total ammoniacal N (TAN), and total Kjeldahl N (TKN) at the University of Wisconsin-Madison Biological Systems Engineering Department water quality laboratory according to USEPA guidelines (Table A.1 found in the appendix).

2.1. Intensively sampled sites

The three sites (A, B, and C) that were intensively monitored over the course of one year were all equipped with an ISCO® Avalanche refrigerated automated sampler (Teledyne Technologies, Inc., Lincoln, NE) with a Bubbler flow module (Teledyne Technologies) to collect runoff samples and monitor flow rates. ISCO samplers were programmed to collect 425 ml discrete samples (2 discrete samples per bottle) at a volume interval required to equally sample runoff produced from a 2 year, 24-h design storm in south central Wisconsin as modeled using HydroCAD-10 (HydroCAD Software Solutions LLC, Tamworth, New Hampshire). Flowrate was continuously monitored and recorded at one-minute intervals.

The main feeds stored at the intensively monitored sites were corn silage and haylage (Table A.2). At site A, surface runoff was collected via gravity into a pit covered with a grate located at the lowest point of the silage storage area. A rectangular weir and sample line were placed within the pit to monitor surface runoff only (excluded subsurface flow in tiles underneath bunker). Site B was designed with no dry weather leachate collection nor a subsurface tile collection system. A Cipolletti weir and the sampling line were placed at the outlet of site B's collection channel at the low point of the pad to measure the flow and collect samples for water quality analysis. The horizontal bunkers at site C had small drains within the bunkers for collection of dry weather leachate. Low points on the feed pad had larger drains to collect runoff. All of the piping from these collection points were routed underground to a single main culvert. At site C the outlet culvert, designed to transfer leachate and runoff to a settling basin before a vegetative treatment area, was used as the control structure for flow measurement and sample collection.

2.2. Composite sampled sites

Composite sampling was used to determine seasonal and annual loading from sites D, E, and F. All three sites (D, E, and F) were monitored with an automated, refrigerated, 24-bottle ISCO® 3700R sampler (Teledyne Technologies, Inc., Lincoln, NE) with sampling methods conducted in accordance with USGS methods (Stuntebeck et al., 2008). Discrete samples collected during flow events were composited based on flow volume for individual events. At Site D, 2673 discrete samples were collected from 10/13/2012 to 12/16/2014 and 498 composite

Table 1
Site characteristics of horizontal dairy bunkers monitored.

Site	Total Feed Storage Area (m^2)	Horizontal Bunker Area (m^2)	Feed Pad Area (m^2)	Contributing Runoff Area (m^2)	Subsurface Collection	Pad Material	No. of Runoff Events Sampled
A	5300	4100	1200	n/a	Yes	Concrete	10
B	2400	1600	800	n/a	No	Asphalt	12
C	7250	4900	2350	n/a	Yes	Concrete	15
D	4675	3565	1110	15,337	Yes	Concrete	84
E	4317	1739	2578	14,164	Yes	Concrete	56
F	777	592	185	2549	Yes	Concrete	44

samples were analyzed; at Site E, 1219 discrete samples were collected from were collected from 1/11/2013 to 12/16/2014 and 299 composite samples were analyzed; and at Site F, 558 discrete samples were collected from 10/13/2012 to 4/25/2014 and 123 composite samples were analyzed. Bunkers at these sites were designed for separate management of silage effluent and silage runoff. Silage effluent would be routed into an initial storage tank, and during a rain event higher flow rates of silage runoff would then overflow these initial collection systems and be routed to a vegetative filter-strip. Two streams existed at these sites; therefore, two composite samples were collected from each storm event in the study to determine the combined loading of low flows of silage effluent and silage runoff. Each site also had two cameras installed to capture photos of the feed storage area and the leachate/runoff collection system in order to assess site conditions. In the final year of the study, a conductivity probe was installed at Site D and E (Decagon Devices, Inc., ES-2 Electrical Conductivity Sensor) (Table A.1). At all sites, low wattage (9.8 W/m) heat tap and pipe insulation ran the length of the sample lines to prevent the line from freezing during the winter.

Corn silage and haylage were the main feeds stored at the composite sampled sites (sites D, E and F) (Table A.3 and A.4). Runoff at site D was transported in a flow channel via gravity (which contains a large picket strainer used to remove large debris) to a 2.6 m^3 collection sump with a 0.1 m pipe at the bottom leading to a 30 m^3 collection tank (Figure B.2 of Appendix B). Liquid from drain tiles both under the bunker and around the perimeter also emptied into the collection tank. To sample overflow runoff at site D a custom designed weir plate with a bubble line was attached to the inside of the concrete cutout in the collection sump. At site E bunkers were sloped to a retaining wall that directs flow to sump pipe through a pipe to a 4.5 m^3 collection tank (Figure B.3). Liquid from drain tiles both under the bunker and around the perimeter also empty into the collection tank. To sample overflow runoff at Site E, an Inline Water Level Control Structure™ (Agri Drain Corporation, Adair, IA, U.S.A.) was installed with a bubble line. Unlike sites D and E, site F did not have a bunker with tile drainage underneath. Site F was graded to transport runoff to a flow channel via gravity that flows through a 3.0 m^3 collection tank (Figure B.4). To sample overflow runoff at site F, a bubble line was attached in the overflow pipe from the collection tank. The internal dimensions of the pipe were used for flow calculations based on depth and slope of the pipe. An area velocity flow meter (Teledyne Technologies) was also installed to measure overflow due to intermittent backwater conditions in the pipe. At site D, E, and F a bubble line was installed in the initial collection tank (0.3 m from the bottom) to monitor flow from this wastewater stream.

2.3. Data analysis

To determine the average nutrient concentrations in silage runoff the event mean concentration (EMC) for each individual storm, or the flow-weighted mean, at each site was calculated using Eq. (1). This value is useful for determining pollutant loads and comparing concentrations of nutrients discharged from silage storage facilities. The EMC allows for water quality comparisons between sites the intensively and composite sampled sites with different runoff rates and volumes.

$$\mathrm{EMC} = \frac{\sum_i^n C_i Q_i \Delta t_i}{\sum_i^n Q_i \Delta t_i} \tag{1}$$

Where EMC is the event mean concentration, t is the time of sampling, C is the nutrient concentration of a sample, Q is the flow rate at the time of sampling.

First flush was previously defined by Gupta and Saul (1996) as a 20% difference between the cumulative mass and cumulative volume in the initial 50% of total volume. To quantitatively determine if a first flush occurred, the Mass First Flush ratio (MFF) for water quality parameters were determined for sites A, B, and C. The MFF quantifies the proportion of cumulative nutrient mass to cumulative volume at a certain point of time throughout the duration of the storm as shown in Eq. (2) (Ma et al., 2004). If $\mathrm{MFF}_{0.5}$ is equal to or greater than 1.4, 70% of the pollutant mass is discharged in the first 50% of the total volume, designating a first flush.

$$\mathrm{MFF_n} = \frac{\dfrac{\int_0^{t1} C(t)Q(t)dt}{M}}{\dfrac{\int_0^{t1} Q(t)dt}{V}} \tag{2}$$

Where MFF is the mass first flush ratio, n is point in the storm ranging from 0 to 100% of total runoff, M is a total mass of discharged pollutants, V is a total runoff volume, C and Q are a pollutant concentration and flowrate of runoff, respectively.

Statistical analysis was performed using the SAS software version 9.4 (SAS Institute Inc., Cary, North Carolina) and R environment version 3.3.2 (R-Core-Team, 2016). Pearson correlation coefficients PCC and p-values (Proc CORR) were calculated for the intensively sampled sites using SAS to identify trends between all water quality parameters measured, flow rate, rain intensity, and nutrient concentrations. To determine statistical differences between EMCs between the bunkers monitored a Kruskal Wallis test for nonparametric analysis was performed using the Agricolae package in the R environment, using an alpha = 0.05 confidence level (De-Mendiburu, 2016). The Kruskal Wallis test was ran separetely for the two types (composite and intensive) of measured sites. To determine statistical seasonal differences in N and P loading from a bunker one-way ANOVA (Proc ANOVA) was calculated using SAS. Seasonal loading analysis was completed on the compositely samples sites. A Student-Newman-Keuls test was conducted to compare differences between seasons at alpha = 0.05 confidence level.

3. Results and discussion

At the intensively monitored sites, correlation was measured between contaminant concentrations; therefore, storm-loading trends will be similar for several parameters, simplifying discussion. PCCs demonstrated significant positive correlation between TAN, BOD_5, COD, and SRP (Tables A.5, A.6, and A.7 of the Appendix). At sites A and B, flow rate was inversely correlated with TAN, BOD_5, COD, and SRP. Chemographs, or the plotted flow rate and nutrient concentration over an individual storm, for a rain event at site A (Fig. 1) illustrate the inverse correlation of water quality parameters with flow rate and the positive correlation between water quality parameters. Low flow rates throughout individual storms had elevated concentrations of nutrients, contrary to a first flush scenario where the initial volume contains a majority of the pollutant load. A majority of the total phosphorus in silage runoff over all storms and sites was SRP, representing 56% to 94% (Table 2). The fraction of TAN in the runoff was 14 to 30% of the TKN (Table 2), reflecting recommended ensiling practices designed to remove oxygen and rapidly drop the pH which will reduce the breakdown of crude protein into ammonia.

3.1. Event mean concentration

As expected, average silage bunker effluent concentrations from all sites were less concentrated than leachate values from literature, as samples consisted mostly of silage runoff which is more dilute from the inclusion of precipitation in contrast to leachate which is produced during ensilage (Table 2) (McDonald et al., 1991) (Table 2). Silage effluent EMCs for TAN and SRP were comparable to previous measurements by Faulkner et al. (2011), monitoring only silage runoff from a bunker. In the current study, the average silage effluent EMCs for TAN from all the sites monitored ranged from 25 to 68 mg L^{-1} of silage effluent in comparison to the bunker monitored by Faulkner et al. (2011) of 59 mg L^{-1} of silage runoff. Site average EMCs for SRP in the current

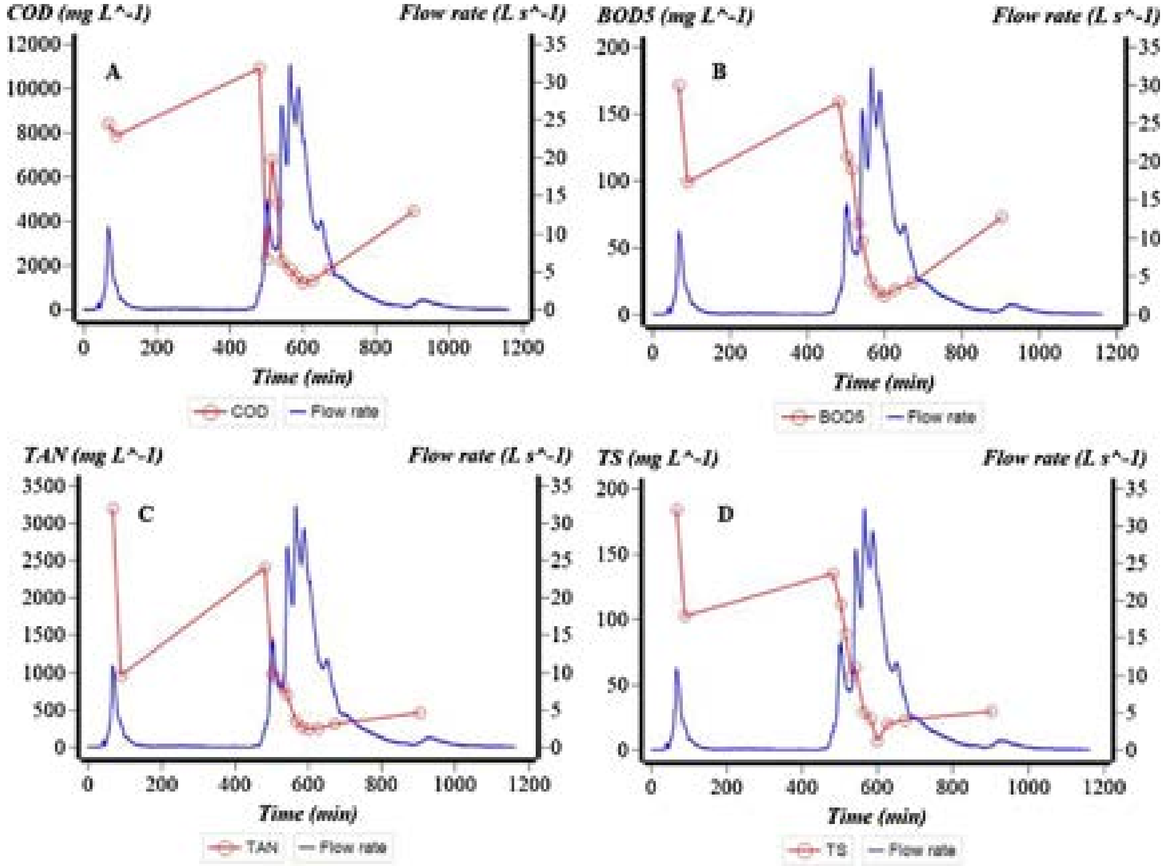

Fig. 1. Flow rate (right vertical axis) and nutrient concentrations (left vertical axis) for COD (A), BOD_5 (B), TAN (C), and TS (D) over an individual storm on 4/28/2012 at site A.

Table 2

Flow-weighted average concentrations from the intensively sampled sites (A, B, and C) and the initial (1) and overflow (2) runoff from the compositely sampled sites (D1, D2, E1, E2, F1, and F2). Measurements with similar letters indicate no statistical difference at the $\alpha = 0.05$ level (Kruskal Wallis tests was ran separately for the composite and intensively sampled sites). Biological oxygen demand (BOD_5), chemical oxygen demand (COD), total phosphorus (TP), soluble reactive phosphorus (SRP), Total Kjeldahl Nitrogen (TKN), total ammoniacal nitrogen (TAN); total solids (TS).

	pH	BOD_5 (mg L^{-1})	COD (mg L^{-1})	TP (mg L^{-1})	SRP (mg L^{-1})	TKN (mg L^{-1})	TAN (mg L^{-1})	TS (mg L^{-1})
Intensively Sampled Sites								
A median	6.36^{b}	1451^{b}	2997^{b}	28^{b}	20^{b}	83^{a}	25^{b}	2847^{b}
Q_1 25th PCTL	5.51	1008	2320	26	19	53	22	2593
Q_3 75th PCTL	6.63	1531	3281	33	23	416	31	3165
B median	5.44^{a}	2733^{a}	6827^{a}	50^{a}	35^{a}	102^{a}	34^{a}	4550^{a}
Q_1 25th PCTL	4.93	2269	3569	47	16	83	22	3843
Q_3 75th PCTL	6.11	4011	7393	54	50	277	47	6739
C median	4.24^{a}	2288^{a}	5899^{a}	44^{a}	39^{ab}	177^{a}	41^{ab}	6908^{a}
Q_1 25th PCTL	4.21	2067	5300	37	29	85	31	4816
Q_3 75th PCTL	5.28	3945	9308	66	60	303	77	10,072
Compositely Sampled Sites								
D1 median	5.41^{abc}		8845^{a}	71^{a}	67^{a}	270^{a}	90^{a}	5854^{a}
Q_1 25th PCTL	5.1		6148	53	49	199	64	4484
Q_3 75th PCTL	5.68		12,658	98	95	378	129	8020
D2 median	5.34^{abc}		5220^{bc}	37^{c}	31^{bc}	175^{cd}	42^{c}	3657^{bc}
Q_1 25th PCTL	5.03		3247	28	24	103	24	2515
Q_3 75th PCTL	5.62		7616	53	48	212	45	5600
E1 median	5.25^{bc}		6225^{b}	46^{b}	38^{b}	205^{b}	63^{b}	4341^{b}
Q_1 25th PCTL	4.89		4650	34	29	159	40	3181
Q_3 75th PCTL	5.74		9330	67	55	275	96	5889
E2 median	5.53^{ab}		3427^{c}	26^{d}	21^{d}	119^{d}	25^{c}	2807^{c}
Q_1 25th PCTL	5.14		2505	21	16	97	18	2002
Q_3 75th PCTL	5.95		4860	32	27	159	37	3618
F1 median	5.54^{a}		5140^{bc}	32^{cd}	27^{cd}	199^{bc}	60^{b}	4100^{bc}
Q_1 25th PCTL	5.23		3195	26	21	113	38	2525
Q_3 75th PCTL	5.97		7491	46	42	266	86	6375
F2 median	5.08^{c}		4800^{c}	35^{cd}	31^{cd}	204^{bc}	33^{c}	3554^{bc}
Q_1 25th PCTL	4.85		2758	26	20	129	24	2138
Q_3 75th PCTL	5.46		6176	42	40	271	57	5550

study ranged from 19 to 70 mg L^{-1} of silage effluent in comparison to an average SRP EMC of 37 mg L^{-1} of silage runoff measured by Faulkner et al. (2011).

In accordance with the inverse correlation of nutrients to flow rate, the EMCs of the high flow runoff (D2 and E2) was lower than the runoff from the initial storm water runoff produced at a lower flow rate (D1 and E1). The magnitude of difference in measured parameters was commonly less than 50% for measured constituents. Conversely, at Site F, nutrient concentrations in the intimal runoff sampled (F1) were not significantly lower than the subsequent runoff (F2), likely due to bunker design. Sites D and E had drain tiles underneath the bunkers and around the perimeter that drained into the tank which likely resulted in additional silage leachate by volume in the low flow. Site F was designed without subsurface tiles below the bunker and less silage leachate could have been included in the sampling tank. Silage leachate at site F could have skirted collection by leaching through the pad prior to rain events. In addition, forage ensiled may have had an effect on low flow nutrient concentrations between the compositely sampled sites. P lost with the low flow runoff at site F was significantly less than the other composite sample sites, sites D and E. Of the total forage ensiled 75% was corn silage at site F in comparison to 48% and 43% for sites D and E, respectively (Appendix B). Corn silage has a lower phosphorous content (0.26% DM) then rye silage (0.42% DM) (National Research Council, 2001).

Silage effluent measured at the intensively manage sites was also impacted by bunker design as a separate subsurface tile collection system for silage leachate at site A reduced nutrient concentrations. Site A had the lowest median runoff nutrient concentrations of the intensively sampled sites (Table 2). The relatively low concentrations at site A were attributed to the collection system monitoring only silage runoff. Subsurface silage leachate was collected and transferred to a manure storage in a separate system, segregated from the monitoring system for silage runoff. Although the silage runoff alone at Site A had lower concentrations than silage effluent sampled at the other sites this wastewater would still impact surface water quality with an average phosphorus EMC concentration 28 fold greater than P discharge limit of 1 mg L^{-1} for Wisconsin Pollutant Discharge Elimination Permits. At animal feed operations that must meet zero discharge, surface runoff produced must completely infiltrate to protect surface waters from P loading, although the elevated nitrogen concentrations must be managed to reduce risks associated with nitrate leaching. Site B had significantly higher BOD_5, COD, TP, SRP, TAN, and TS concentrations than site A (1.8, 2.3, 1.8, 1.7, 1.4, and 1.6 fold greater, respectively). Site B had higher nutrient concentrations than site A due to the inclusion of silage leachate. Although no subsurface drainage was present for the bunkers at site B, silage leachate was transferred by gravity over the surface of the bunker and this stream was visibly present before storm events, particularly in the fall. Effluent collected at site C included subsurface flows from tile drains underneath the bunker and also had significantly higher runoff concentrations of BOD_5, COD, TP, and TS than site A (1.6, 2, 1.3, and 2.4 fold greater, respectively). At the intensively sampled site there was no additional differences in feed characteristics or climate, that could explain dissimilarities in effluent concentrations. Notably, concentrations of TKN were statistically similar between intensively sampled sites.

3.2. Seasonal differences in runoff concentration and loading from year-round sampled sites

Sites D, E, and F had similar seasonal trends in runoff N and P concentration throughout the year; however, the low flow collected in the storage tanks was affected by the amount of forage stored and seasonal silage leachate production. For simplicity, the measured concentrations at Site F from October 2012 to November 2013 are provided in the main text (Fig. 2) and the other two sites are provided in the Appendix (Figures B.5 and B.6). Concentrations of N and P in the low flow runoff increased as much as 144% (197% higher than the EMC for TP and TKN, respectively) in mid to late November. Low flow runoff produced during this period has a greater possibility of incorporating nutrients from silage leachate, as a final cut of hay is ensiled in August and corn is ensiled in September. Silage leachate is produced during the fermentation phase of forage, two to 14 days after ensilage (Pitt, 1990). Therefore, low flow runoff produced after September will have a greater chance of incorporating leachate. Although, measured concentrations did not increase until a month or two after the ensilage of forage (Fig. 2). It is likely, a portion of silage leachate produced after ensilage could require bunker disturbances, such as feed out, to be released and incorporated in runoff.

A more diluted low flow runoff occurred in August and early September (Fig. 1). Feed storage bunkers had the lowest amount of forage during this time of year, as the majority of forage was ensiled (corn silage) in mid to late September, impacting the amount of nutrients available to be lost as runoff. Low flow silage runoff is relatively inconsistent over winter months, as seen for site D, as no apparent trends existed (Fig. 3). Snowmelt did result in concentrated N and P in high flow silage runoff as TP and TKN concentrations doubled the EMC in early April when the average temperature for the week rose above 4 °C (Fig. 3). Silage that is removed from the feed-out face but is left behind as surface litter during loading adds nutrients to the bunker area. During the winter, nutrients from the surface litter and silage leachate may accumulate as it is often immobilized with ice and snow accumulations. A rain event or snowmelt likely releases these built up nutrients during cold periods over the first few runoff events resulting in higher runoff concentrations.

Overall, seasonal variability in runoff produced from feed storage areas is too low for seasonal collection to have impact on annual loading. Seasonal differences in loading only occurred for site D where average summer TP storm event loading was 50% higher than in the fall and winter (Figure B.5 found in Appendix), although this site was the only site with winter monitoring. Higher TP loading during this time was due to a combination of more concentrated runoff in the summer and larger runoff volumes. At all three sites, TKN loading was not significantly impacted by seasonality.

3.3. First flush effect from intensively sampled sites

$MFF_{0.5}$ at all sites ranged from 0.68 to 1.58 on average for all measured water quality parameters, Fig. 4. The average $MMF_{0.5}$ for TKN at sites A, B, and C was much less than the 1.4 required (1.06, 1.08, and 1.03, respectively) for a defined first flush of 20% difference in load and volume (Gupta and Saul, 1996). The average $MMF_{0.5}$ for TP at sites A, B, and C was also less than 1.4 (1.0, 1.10, and 1.08, respectively). Site A (silage runoff alone) often had MMF ratios less than 1 indicating some delayed loading. Silage litter and nutrients may migrate from the bunker to the pad with higher rates of runoff. Sampling at site C included silage runoff and leachate which resulted in the absence of the delayed load pattern as subsurface leachate generally increases nutrient concentration due to lack of dilution water.

The inverse correlation of water quality parameters BOD_5, COD, SRP, TKN, TP, and TS with flow rate supports the uniform loads measured. Even though the initial runoff was more concentrated than the subsequent high flows, nutrients available for runoff incorporation were consistent, resulting in the persistence of a concentrated runoff during lower flow rates at the end of the storm. This is in contrast to a first flush scenario where the initial wastewater is more concentrated than the entire remainder of the storm. In a first flush scenario, impervious surfaces create high velocities that easily scours and transports pollutants from surfaces and will occur almost immediately at the beginning of rainfall. Impervious areas with documented first flush scenarios include parking lots (Schiff et al., 2016), roads (Cheng et al., 2017; Stenstrom and Kayhanian, 2005), industrial areas (Li et al., 2015), and residential communities (Lee et al., 2002) where there

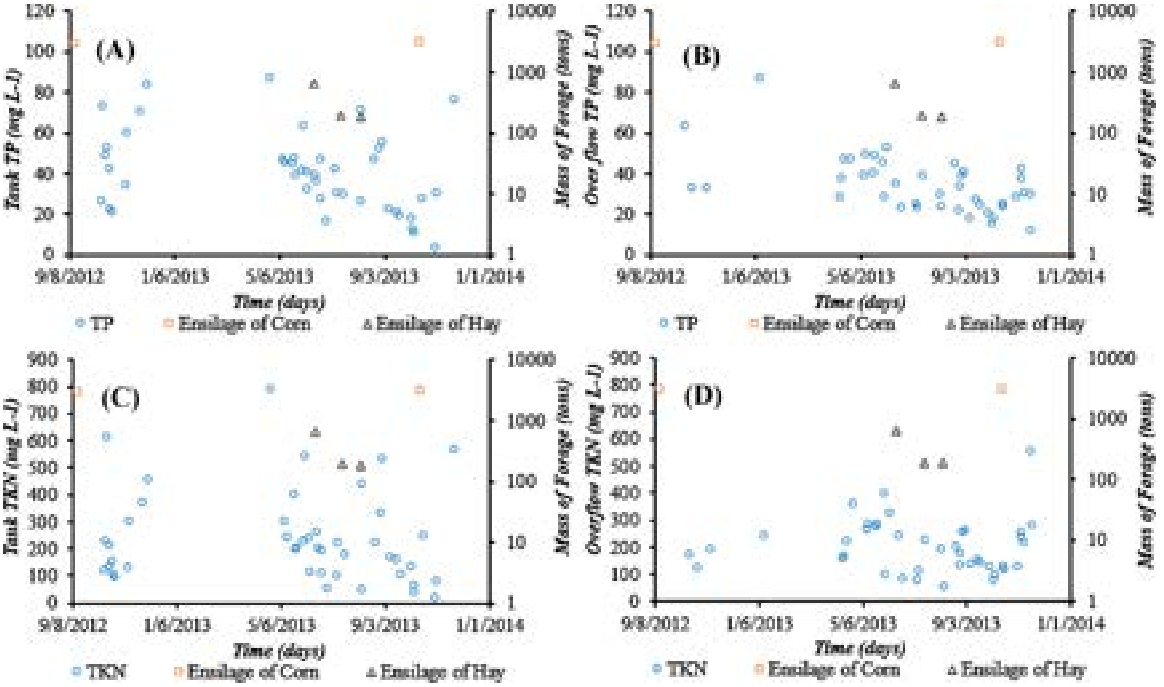

Fig. 2. Site F tank and overflow TP and TKN (left vertical axis) with mass ensiled forage (right vertical axis) over monitoring period. (A) Tank TP; (B) overflow TP; (C) tank TKN; (D) overflow TKN.

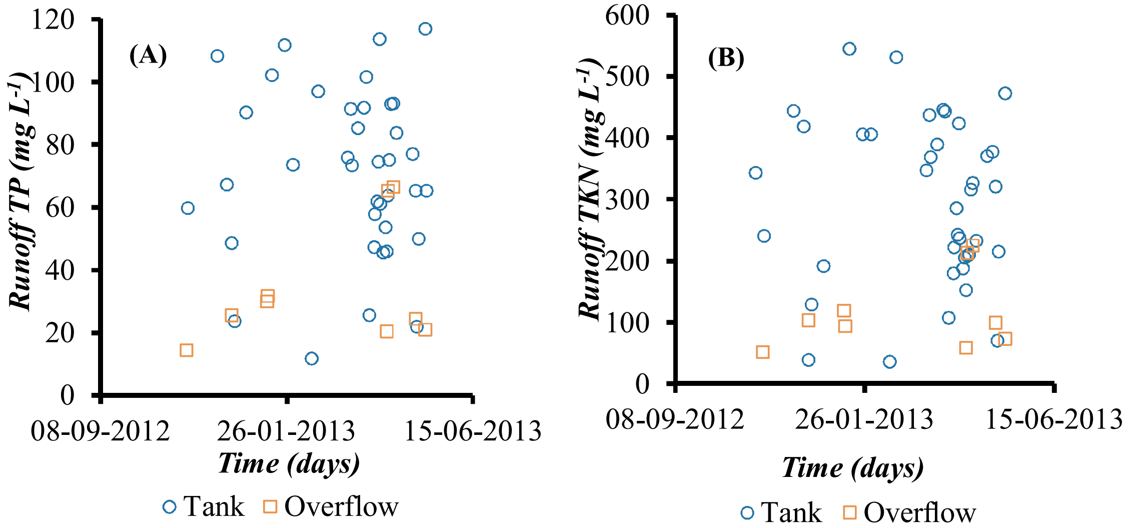

Fig. 3. Site D tank and overflow TP and TKN from winter runoff events; (A) TP and (B) TKN.

contaminant pool could be considered finite. In contrast, silage storage areas may be a continued source as nutrients are likely released from the bunker piles throughout the storm as rainwater dissolves nutrients and solids in rainwater. Therefore, a silage effluent wastewater treatment system designed to collect a first flush will not result in a higher nutrient loading captured, as the concentrations of low flow runoff at the end of a storm event remain concentrated (Table 3).

3.4. Annual loading from composite sampled sites

Annual loading ranged from 119 to 435 kg P per ha and 1627 to 2184 kg N per ha of contributing area, making effluent from silage bunkers one of the highest concentrated runoff nutrient loss areas on a farm in terms of loading per unit area. In comparison, the sum of simulated P losses (including dissolved surface runoff, leachate, sediment runoff, and windborne sediment) from crop fields in the U.S. are estimated to be 1.0 to 4.8 kg per ha annually (Potter et al., 2006). Notably, the contributing runoff area used to calculate these numbers is three to four times greater than the feed storage area. Therefore, it is likely that runoff generated from the contributing areas surrounding the bunker generate a more dilute runoff likely resulting in an underestimation of load. Using the quantity of forage ensiled at each site (Tables A.3 and Table A.4) and the N and P content for each respective nutrient content (National Research Council, 2001), the initial mass of N and P ensiled was calculated for sites D, E, and F. Based on estimates of the ensiled nutrient content, annual silage effluent losses of P and N from these sites were 0.3% to 1.8% and 0.4% to 1.7% of the initial nutrient mass ensiled, respectively. The greatest loss percentages were from the site with the greatest generated volume of runoff (site E in year 2).

In order to better compare runoff nutrient losses at the farm scale, a theoretical WI farm, as defined by Powell et al. (2005) which assumed a

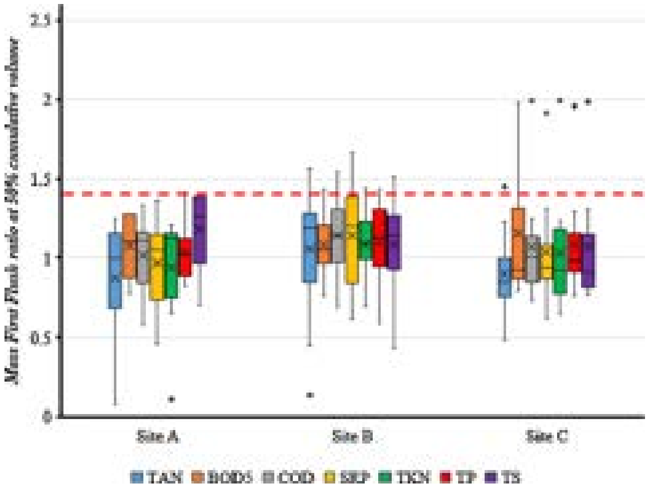

Fig. 4. Box and whisker plot of Site A, B, and C $MFF_{0.5}$ ratios of TAN, BOD_5, COD, SRP, TKN, TP, and TS. The X represents the average $MMF_{0.5}$ ratios for each parameter. The horizontal line within the box indicates the median $MMF_{0.5}$, boundaries of the box indicate the 25th- and 75th −percentile, and the whiskers indicate the highest and lowest $MMF_{0.5}$. The red dashed line represents a $MMF_{0.5}$ threshold of 1.4 required for a first flush. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

herd of 52 lactating cows, 9 dry cows, 15 young heifers, and 28 mature cows with a total cropping area of 80 ha, was used to estimate N and P losses from a variety of runoff sources (Table 4). In this assessment P loss from corn grain and alfalfa was assumed to be 75% and 50% of P and N loss from corn silage, respectively (Bormann et al., 2012; Wendt and Corey, 1980). The theoretical bunker area was calculated by averaging the number of cows per area from the six sites and multiplying by the theoretical herd size. Average P and N loads from the composite sampled sites was used to calculate the amount of P and N lost from the theoretical area.

Given these assumptions and results, the average bunker area in WI would contribute as much as 30% and 55% of total P and N losses from dairy farm runoff. This may be conservative as the total feed storage area for the theoretical farm was calculated based on the average feed storage area across the six sites. However, the nutrient concentration was based on the total contributing area which in most cases likely diluted the nutrient concentrations. While nutrient losses between dairy farms may vary considerably due to topography, cropland soil properties, management practices, and the ratio of field area to farmstead. This assessment shows the magnitude of the losses from feed storage areas, which may constitute a very small portion of the land area; therefore, increased management of these areas provides an opportunity to reduce nutrient loading from farmstead runoff and increase nutrient use efficiency.

3.5. *Design considerations for runoff collection*

Calculated and measured nutrient losses from horizontal bunkers and pads is a large fraction of nutrient losses from a dairy facility, highlighting the need for management. Constructing a roof over bunker silos and feed pad areas would prevent formation of silage runoff, although leachate collection would still be necessary. When a roof is not feasible, collection system designs should focus on collecting low flows throughout the storm which have the highest concentrations, generally occurring at the beginning and end of storm runoff. While collecting low flows would be beneficial, it may be hard to design site specific systems without thorough investigation into the flow rates produced with either software of monitoring equipment.

An alternative design could utilize conductivity probes to segregate high concentrated runoff. Linear regression models were developed to predict TAN, TKN, TP, and SRP concentrations of runoff from conductivity measurements (R^2 of 0.65 to 0.80), Fig. 5. Formulas (1), (2), (3), and (4) predict TAN, TKN, TP and SRP ($\mathrm{mg\,L^{-1}}$) according to measured conductivity ($\mu\mathrm{S\,cm^{-1}}$), respectively, where x = electric conductivity ($\mu\mathrm{s\,cm^{-1}}$).

$$TKN = 0.84x - 5.25 \quad R^2 = 0.80 \tag{1}$$

$$TAN = 0.23x - 0.64 \quad R^2 = 0.65 \tag{2}$$

$$TP = 0.40x - 38.61 \quad R^2 = 0.80 \tag{3}$$

$$SRP = 0.34x - 28.00 \quad R^2 = 0.74 \tag{4}$$

All parameters had significant positive regression weights indicating higher measurements of conductivity resulted in runoff with higher concentrations of TAN, TKN, TP, and SRP. Equations relating nutrient concentration to the conductivity reading could be used to set a minimum or maximum real-time concentration that would trigger a collection system. Conductivity probes are generally more robust than other available nutrient sensors and remained functional for the year that they were used in the field for this study.

4. Conclusions

Silage runoff was intensively and extensively monitored for first flush analysis and to determine the impact of site design and seasonal differences from forage type and quantity on nutrient concentrations and annual loading. Measured water quality parameters BOD_5, COD, SRP, TKN, TP, and TS were inversely correlated to flow rate and a uniform loading curve was prevalent as nutrient availability did not reduce over the event. Low flow nutrient concentrations were impacted by silage leachate production where bunker designs removing silage leachate resulted in overflow runoff with a higher water quality than sites without subsurface collection. If not managed properly silage runoff has the potential to be a major contributor to P and N losses from dairy farms and technologies or practices for abatement has strong potential for improved nutrient management.

Table 3
P and N losses, runoff area, and volume from the composite sampled sites.

Site	Runoff Area (m^2)	Total Annual Runoff Volume (m^3)	Runoff (mm)	Annual P Loss (kg P)	Annual N Loss (kg)	Annual P Loss per Area ($\mathrm{kg\,ha^{-1}}$)	Annual N Loss per Contributing Area ($\mathrm{kg\,ha^{-1}}$)
D year 1[a]	15,337	8664	565	357	1530	233	1766
D year 2[a]	15,337	10,689	697	668	2334	435	2184
E year 1[b]	14,164	6656	470	298	1276	211	1918
E year 2[b]	14,164	11,454	809	505	1873	357	1635
F year 1[c]	2549	1048	411	30	170	119	1627
Average						271	1826

[a] Estimated average P and N in bunkers at site D was 70,300 kg and 271,200 kg, respectively.

[b] Estimated average P and N in bunkers at site E was 27,500 kg and 110,200 kg, respectively.

[c] Estimated average P and N in bunkers at site F was 9900 kg and 40,000 kg, respectively.

Table 4

Theoretical farm runoff N and P losses (theoretical farm of 52 lactating cows, 9 dry cows, 15 young heifers, and 28 mature cows and a total cropping area of 80 ha).

Farmstead Location	Theoretical Area (ha)	Annual P Loss per Unit Area (kg ha^{-1})	Annual N Loss per Unit Area (kg ha^{-1})	Total Farm P Lost (kg P)	Total Farm N Lost (kg N)
Vegetated feedlot	6.5[*]	1[+]	3[+]	7	20
Partially vegetated feedlot	2.0[*]	2[+]	7[+]	4	14
Un-vegetated feedlot	0.7[*]	100[†]	29[+]	70	20
Cropland					
Corn silage	11.0[*]	2[+]	7[+]	22	77
Corn grain	15.0[*]	2[+]	5[+]	30	75
Alfalfa cropland	25.0[*]	1[+]	4[+]	25	100
Other cropland	31.0[*]	1[a]	4[a]	31	124
Pasture	4.0[*]	1[b]	3[b]	4	12
Total feed storage area (horizontal bunker and pad)[a]	0.3[c]	271	1826	81	548
Total				274	990

[*] Powell et al., 2005.

[+] Vadas and Powell, 2013.

[†] Vadas et al., 2015.

[a] Estimated based on the average nutrient loss from alfalfa cropland.

[b] Estimated based on the average nutrient loss from vegetated feedlot.

[c] Based on an average horizontal bunker area of 5.4 m^2 per lactating cow for the six study sites.

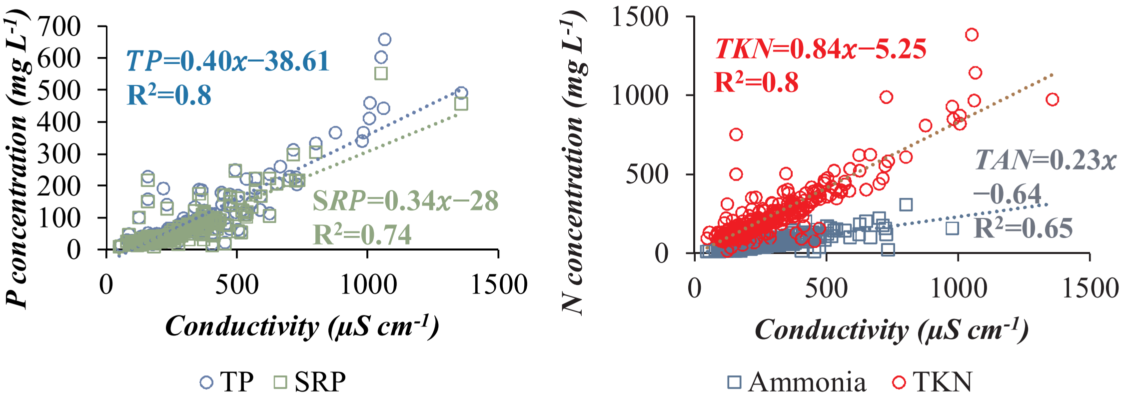

Fig. 5. P and N relationship to conductivity.

Acknowledgements

This material is based upon work supported by the University of Wisconsin Water Resources Institute through the Wisconsin Groundwater Coordinating Council. We would like to thank Todd Stuntebeck of the U.S. Geological Survey for his assistance with monitoring components of the composite sampled sites.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2018.05.015.

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