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Research Article

Comparison of Raw Dairy Manure Slurry and Anaerobically Digested Slurry as N Sources for Grass Forage Production

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We conducted a 3-year field study to determine how raw dairy slurry and anaerobically digested slurry (dairy slurry and food waste) applied via broadcast and subsurface deposition to reed canarygrass (*Phalaris arundinacea*) affected forage biomass, N uptake, apparent nitrogen recovery (ANR), and soil nitrate concentrations relative to urea. Annual N applications ranged from 600 kg N ha^{-1} in 2009 to 300 kg N ha^{-1} in 2011. Forage yield and N uptake were similar across slurry treatments. Soil nitrate concentrations were greatest at the beginning of the fall leaching season, and did not differ among slurry treatments or application methods. Urea-fertilized plots had the highest soil nitrate concentrations but did not consistently have greatest forage biomass. ANR for the slurry treatments ranged from 35 to 70% when calculations were based on ammonium-N concentration, compared with 31 to 65% for urea. Slurry ANR calculated on a total N basis was lower (15 to 40%) due to lower availability of the organic N in the slurries. No consistent differences in soil microbial biomass or other biological indicators were observed. Anaerobically digested slurry supported equal forage production and similar N use efficiency when compared to raw dairy slurry.

1. Introduction

There is a need for a set of best management practices that addresses how to utilize the growing quantity of reactive nitrogen (N) produced by livestock operations. Animal agriculture in the United States has become more specialized with farms consolidating and growing in size [1]. The number of dairy farms has decreased by 94% since 1960, but the number of animals has remained constant [2]. Animal consolidation has created challenges with respect to on-farm N surplus, waste management and nutrient loading in the environment [3, 4]. Annually in the United States, more than 5800 Mg of manure N is produced [5]. One approach to ameliorate negative environmental impacts associated with animal manures is through adoption of anaerobic digestion technologies to treat farm-generated manures and food processing wastes [6–9]. Digestion of wastes can provide a stable and consistent source of nutrients comparable to inorganic fertilizers such as urea.

Anaerobic digestion converts organic carbon into methane used to generate electricity, and it also converts organic N to plant available ammonium (NH_4^+), increasing the ratio of NH_4^+/total N in the effluent [10]. Carbon is removed during both the methane production and fiber removal processes, resulting in a smaller C : N ratio of the effluent [11]. Therefore, digested effluent can serve as low-cost source of readily available nutrients for crop production. Some studies [12] have found increased yield and N availability with application of anaerobically digested material as compared to nondigested material, possibly due to increased N availability and reduced carbon (C) content. Anaerobically digested manure can provide sufficient nutrients to support biomass and crop yields equivalent to synthetic fertilizers and raw manures [13, 14]. The apparent mineral nitrogen recovery

(ANR_M) of tall fescue (*Festuca* spp.) receiving raw dairy manure slurry was reported by Bittman et al. [13] as 55 and 51% at early and late applications, respectively, using the drag shoe method (band applied directly to soil, under plant canopy). When surface applied, the ANR_M was 37% applied early and 40% when applied late. Similar results were presented by Cherney et al. [15] with orchardgrass (*Dactulis glomerata* L.) and tall fescue.

Perennial systems that contain living plants year round tend to remove more reactive N than annual systems. Mean reed canarygrass biomass measured in trials in Minnesota was 13 Mg ha^{-1} under modest N applications (168 kg N ha^{-1} yr^{-1}) [16]. Bermudagrass (*Cynodon* spp.) fertilized with 89–444 kg manure N ha^{-1} yielded a mean of 7.92 Mg dry matter ha^{-1} over four or five cuttings per year [17]. However, the forage crop recovered only 25% of the N applied over the four years included in the study. Reed canarygrass (*Phalaris arundinacea*) is an ideal candidate for N removal because of its ability to store any left-over N applied during the growing season in rhizomes overwinter, providing a significant advantage to the forage in early spring when soil-N may be limited [18].

As with any N source, application of manure N in excess of crop uptake can result in NO_3^- leaching [19]. Up to 46% of applied manure N may persist in the soil, increasing the potential for loss of N after multiple applications in a growing season [20]. Some studies indicate that manure N poses less of a risk to leaching than the same amount of N in the form of synthetic fertilizer [21] due to immobilization of N that often occurs as humic materials build up in soil. Other researchers have determined manure increases NO_3^- leaching [22]. Irrespective of the source and properties of the N fertilizer applied during winter months when plants are dormant, NO_3^- leaching can be the main source of N loss [23].

Manure additions can enhance soil fertility and quality through their short and long-term contribution to soil C and N [24–27]. Current research demonstrates that long-term manure applications increase soil organic matter, basal respiration, microbial biomass, and enzymatic activity (measures of soil quality), while mineral fertilizers can decrease pH, enzymatic activity, and microbial biomass C [28]. Organic amendments such as manure also have an effect on microbial community structure in addition to enhancing the activity, C content, and size of soil microbial biomass [29, 30]. A study by Zhong et al. [31] demonstrated total phospholipid fatty acid (PLFA), gram-negative, and actinobacterial PLFA were highest in treatments of organic matter and organic matter + mineral NPK fertilizer. Functional diversity from organic manure and organic manure + mineral NPK fertilizers increased over time far more than with additions of synthetic fertilizers alone. We anticipate that long-term application of raw dairy slurry and digested slurry will enhance soil quality affecting microbial community structure and activity overtime.

The goal of this study was to determine the fate of applied N in anaerobically digested slurry (derived from mixed dairy slurry and food waste), raw dairy slurry, and urea during forage production. Specifically, we compare the biomass, ANR and N uptake of forages to determine which N source(s) has the potential to maintain forage biomass and reduce reactive N. In addition, we evaluated the effectiveness of subsurface deposition versus broadcast application of raw slurry and anaerobically digested slurry to improve forage biomass production, ANR and N uptake of forages, as well as reduce residual reactive N. Our hypotheses were (1) digested slurry would have more available N and generate a greater forage response than raw slurry, (2) subsurface deposition would conserve more N than surface application, resulting in greater forage response, particularly for the raw manure with higher solids content, and (3) application of digested slurry would reduce soil nitrate-N concentrations relative to urea.

2. Materials and Methods

2.1. Site Description. A field-based experiment, located on a commercial dairy in Monroe, Washington, was established in 2009. The field was mapped as 90% Puget silty clay loam (fine-silty, mixed, superactive, nonacid, mesic Fluvaquentic Endoaquepts) and 10% Sultan silt loam soils (fine-silty, isotic, mesic, Aquandic Dystrochrepts) [32] and had a history of manure applications. The site had climatic conditions typical of the Maritime Pacific Northwest with cool wet winters and dry summers. The 2009 growing season had a drier than normal summer, while 2011 had a cool spring and dry summer (Table 1). The 2010 season had the best growing conditions, with a warm spring and more summer rainfall than 2009 or 2011.

The experimental design included six treatments in a randomized complete block design with four replicates (3.6 m × 18 m). Treatments included two dairy manure slurries (raw and anaerobically digested), two slurry application methods (broadcast and subsurface deposition), inorganic N (pelletized urea), and a zero-fertilizer treatment that received 0 kg N ha^{-1}.

The raw dairy slurry was flushed from the barn floor and obtained fresh from a holding tank. Digested slurry was produced in an anaerobic digester with a plug-flow design, operating within mesophilic (23.5°C) conditions, with an approximate 17-day retention time, and storage capacity of ~6,100,000 liters. Liquid slurry from a single dairy consisting of 1,000 lactating cows was codigested with pre-consumer food-waste substrates. Food-waste consisted of no more than 30% of the total digester input and included whey, egg byproduct, processed fish, ruminant blood, biodiesel byproduct, and Daf grease (dissolved air flotation). After digestion, materials were passed through a rotating drum screen solid separator where solids were removed for composting and liquids pumped to a storage lagoon. The digested slurry applied to plots was obtained just after liquids-solids separation and prior to lagoon storage. A 250 mL subsample of each slurry was taken during each application (Table 2), cooled, and analyzed for total-nitrogen, nitrate-N, ammonium-N, total-phosphorus, and total solids [33] (Table 3).

Table 1: Average air temperature and total precipitation by month beginning at the start of plot implementation through the 3rd growing season.

Year	Month	Average air temp (°C)	Total precipitation (mm)
2009	April	9.2	61
	May	12.8	73
	June	**16.8**	**19**
	July	**20.0**	**6**
	August	**18.0**	**13**
	September	15.5	54
	October	9.9	100
	November	7.6	137
	December	1.4	35
2010	January	7.3	89
	February	7.0	44
	March	7.8	54
	April	9.4	55
	May	11.2	66
	June	**14.4**	**61**
	July	**17.0**	**7**
	August	**17.1**	**22**
	September	15.3	85
	October	10.6	85
	November	5.7	107
	December	5.3	184
2011	January	5.1	120
	February	3.4	80
	March	7.1	119
	April	7.2	79
	May	10.6	74
	June	**14.1**	**39**
	July	**15.7**	**18**
	August	**16.4**	**3**
	September	15.5	23
	October	10.2	71

Data from Washington State University AgWeatherNet, 21-Acres Station.

Table 2: Dates of forage harvest and fertilizer (slurry and urea) applications for field study in Monroe, WA for 2009–2011.

2009		2010		2011	
Forage Harvest	Fertilizer application[a]	Forage Harvest	Fertilizer application[a]	Forage harvest	Fertilizer application[a]
	17-Apr-09[b]		4-Mar-10		
7-May-09[c]	14-May-09	26-Apr-10	11-May-10	5-May-11	19-May-11
2-Jun-09	8-Jun-09	10-Jun-10	22-Jun-10	10-Jun-11	22-Jun-11
1-Jul-09	20-Jun-09[d]	7-Jul-10	15-Jul-10	14-Jul-10	4-Aug-11
28-Jul-09	11-Aug-09	12-Aug-10		22-Aug-10	31-Aug-11
31-Aug-09		15-Sep-10	30-Sep-10	20-Sep-10	
29-Sep-09		2-Dec-10		18-Oct-11	
30-Nov-09					

[a] Soil samples taken 1-day prior to fertilizer application.
[b] Early season manure application by grower, prior to plot establishment.
[c] Harvest prior to plot establishment, yield data from this harvest does not include replicates.
[d] Unintended slurry application from grower.

Table 3: Annual mean N and P concentrations of raw and anaerobically digested slurries applied to pasture plots.

	2009		2010		2011	
	Raw dairy Slurry	Digested slurry	Raw dairy slurry	Digested slurry	Raw dairy slurry	Digested slurry
Percent Total Solids (%)	2.8	1.9	3.4	2.0	3.4	1.4
Total N, mg kg^{-1a}	1441	1617	1653	2672	1475	2000
NH_4–N, mg kg^{-1}	707	1038	776	1253	760	930
Organic N, mg kg^{-1b}	734	578	877	1419	715	1070
Total P, mg kg^{-1}	350	300	331	292	330	210

[a] N and P concentrations reported as is.
[b] Organic nitrogen (N) = total N − NH_4–N.

A mix of reed canarygrass (*Phalaris arundinacea*) cv. "Palaton" and white clover (*Trifolium repens*) was overseeded into the field at 62 kg ha^{-1} in May 2006, three years before the start of this experiment. Plots were sprayed with broad leaf herbicides on 18 June 2009, 10 July 2010, and 8 August 2011 with 1.17 L ha^{-1}, 2, 4-Dichlorophenoxy acetic acid, 73 mL ha^{-1} Carfentrazone-ethyl (*Aim*), and 410 mL ha^{-1}, dicamba (*Banvel*) to control the clover.

2.2. Slurry Application Method. Slurries were applied via two application methods, subsurface deposition and surface broadcast application. Subsurface deposition was accomplished with a 4169-liter capacity manure tank fitted to a National Volume Equipment pump (model MEC 4000/PALD) with a 3.05 meter Aerway Sub-Surface Deposition (Model AW1000-2B48-D) and custom Banderator attachment for application of manure through eight PVC pipes attached directly behind the Banderator tines. Tines were set 19 cm apart on the roller and allowed to drop 10 cm below the soil surface creating intermittent slices 12.5 cm in length at the surface. Visual observation of the plots suggested that the tines created slices at random locations throughout the growing season. Surface broadcast of raw and anaerobically digested slurries were accomplished using an Aerway system with the tines raised above the soil surface.

Application rates for the raw and anaerobically digested slurry were projected to be equal in total N and allowed to vary in ammonia-N, for a total yearly application of approximately 600 kg N ha^{-1} in 2009, 500 kg N ha^{-1} in 2010, and 300 kg N ha^{-1} in 2011 (Table 4). We reduced the amount of N applied on urea and slurry treatments each year of the study from 2009 to 2011 based on the fall soil nitrate concentrations. When soil nitrate-N is above 35 mg N kg^{-1}in the fall, it is recommended that applications be eliminated after August 1st, N application rates be reduced in the subsequent year by 25–40 percent and sidedress N at planting be eliminated [34]. An early season raw dairy slurry application (Table 2, application 1 in 2009) was applied by the grower to all plots prior to establishment of the field plots and is not included in the statistical analyses. An inadvertent application of 143 kg N ha^{-1} across all plots by the grower in June of 2009 (Table 2, application 4) is included in the analysis. This accounts for the higher annual application rate in 2009. Application rates were lowest in 2011 because wet conditions prevented an early season application (Table 4), and the slurries had lower mean N concentrations. Plots were fertilized no more than five days after grass harvest. There were a total of five manure applications per year during 2009-2010 and four in 2011 (Table 2).

2.3. Field Management and Analysis. The aboveground biomass from grass swaths, 0.6 × 0.6 m, was harvested from the center of each plot every 28–35 d (Table 2) using hand-held hedge clippers. Three subsamples were taken within each of the four plot replicates for each treatment. The three subsamples were divided into grasses, clover, and weeds to adjust the aboveground biomass and ANR measurements. Due to herbicide applications, weeds were minimal all years. White clover biomass was significant in two of the cuttings in 2011. Samples were bagged, and weighed immediately. Forage was then dried at 55°C for 24 hrs, weighed, and ground in a Wiley Mill (Arthur H. Thomas Co., Philadelphia, PA) with a 1 mm screen. Ground samples were analyzed for forage nitrogen content with a Leco FP-528 Nitrogen Analyzer (Leco Corporation, St. Joseph, MI; AOAC, 2001) by Cumberland Valley Analytical Services Inc. (Hagerstown, MD).

Soil samples were collected from each plot and analyzed for Bray-1 P, exchangeable K, and pH at the beginning of the experiment 2009 and again at the end of 2010. Six soil cores per plot were taken to a 30-cm depth using a 2.54 cm diameter soil sampling probe and composited. Additional soil samples were collected for nitrate-N analysis monthly throughout the growing season using the same method, except for biweekly from mid-September through the end of November. Nitrate-N below the 30 cm depth was not measured. Soil chemical properties were analyzed by Soiltest Farm Consultants (Moses Lake, WA) using the methods of Gavlak et al. [33]. Ammonium-N was determined using a salicylate-nitroprusside method and nitrate-N using the cadmium reduction method. Soil samples for gravimetric water content were homogenized by mixing, and a subsample was dried at 38°C for 72 hrs [35].

Whole-soil phospholipid fatty acid (PLFA) procedures generally followed Bligh and Dyer [36] as described by Petersen and Klug [37] and modified by Ibekwe and Kennedy [38]. Fatty acid methyl esters were analyzed on a gas chromatograph (Agilent Technologies GC 6890, Palo Alto, CA)

Table 4: Application rate of fertilizer source at each application period, and seasonal total N and P inputs, 2009–2011.

Application	1	2	3	4	5	1	2	3	4	5	Seasonal total		
	Total N kg ha^{-1}					NH_4^+–N kg ha^{-1}					Total N kg ha^{-1}	NH_4^+–N kg ha^{-1}	Total P kg ha^{-1}
2009													
Control	111[a]	0	0	143[b]	0	51	0	0	83[b]	0	254	135	0
Urea	111[a]	112	112	143[b]	112	51	112	112	83[b]	112	590	471	0
Raw	111[a]	121	168	143[b]	47	51	64	78	83[b]	23	590	300	130
Digested	111[a]	176	115	143[b]	81	51	114	93	83[b]	47	626	389	121
2010													
Control	0	0	0	0	0	0	0	0	0	0	0	0	0
Urea	112	112	112	112	0	112	112	112	112	0	448	448	0
Raw	92	112	113	99	84	53	24	58	53	53	500	240	92
Digested	86	121	63	67	129	55	40	35	40	98	466	268	54
2011													
Control	0	0	0	0	0	0	0	0	0	0	0	0	0
Urea	0	112	112	112	0	0	112	112	112	0	336	336	0
Raw	0	52	60	84	63	0	34	24	29	47	258	135	51
Digested	0	33	136	69	70	0	23	52	33	27	308	134	26

[a] Early season slurry application by grower, prior to plot establishment.
[b] Application 4 in 2009 was an unintended application from the grower to all plots. Urea fertilizer considered equal to NH_4^+ in plant availability.

with a fused silica column and equipped with a flame ionizer detector and integrator. ChemStation (Agilent Technologies) operated the sampling, analysis, and integration of the samples. Extraction efficiencies were based on the nonadecanoic acid peak as an internal standard. Peak chromatographic responses were translated into mole responses using the internal standard and responses were recalculated as needed. Microbial groups were calculated based on the procedure of Pritchett et al. [39].

2.4. Slurry Analysis. Slurries were analyzed for total N, ammonium-N, and total P (Table 3). Nitrogen was extracted via the Kjeldahl method [33]. Phosphorus was analyzed using a Thermo IRIS Advantage HX Inductively Coupled Plasma (ICP) Radial Spectrometer (Thermo Instrument Systems, Inc., Waltham, MA) by the Dairy One Forage Analysis Laboratory (Ithaca, NY).

2.5. Statistical Analyses and Calculations. An analysis of variance (ANOVA) was run using SAS PROC MIXED on the aboveground forage biomass, nitrogen content in forage, soil nitrate-N, and soil biological groups for all treatments across the three years [40]. Data were analyzed as a randomized complete block design with each of the six treatments analyzed independently. Crop biomass and crop-nitrogen content from each year were analyzed separately using ANOVA with treatment and sample day as fixed effects. Significance is indicated with a $\rho < 0.05$ [40].

Forage apparent N recovery (ANR%) was calculated in 2010 and 2011 as a percentage of N (total and inorganic) applied during the season based on the work of Cogger et al. [41] and Bittman et al. [13]:

$$100 \times (\text{annual grass N uptake, treated}) - (\text{annual grass N uptake, control})/\text{applied N}. \tag{1}$$

Estimates of N fixed in white clover were set to 80% of total N in clover biomass based on ^{15}N studies conducted in a pasture of similar forages and N fertilizer management [42]. Using the above correction, 80% of clover N was subtracted from the forage N uptake values used in the ANR calculations for the two cuttings in 2011 with significant amounts of clover.

3. Results

3.1. Baseline Soil Data. Soil data sampled in May 2009 prior to the start of the field experiment (Table 5) indicated that fertility was not different across the field site. Organic matter, a source of inorganic-N, averaged 5.5 percent (55 g kg^{-1}). Bulk density of soils in the field ranged from 1.14 to 1.30 g cm^{-3}, with a mean average density of 1.21 g cm^{-3}.

3.2. Forage Biomass, N Uptake and ANR. Analysis of variance results for cumulative forage biomass in 2009 to 2011 are presented in Table 6. Total yield was greatest in 2010 (14.1–18.0 Dry Mg ha^{-1}) and lowest in 2011 (9.2–11.1 Dry Mg ha^{-1}). The 2009 data (8.08–9.5 Dry Mg ha^{-1}) did not include the first cutting of the year (7.7 Mg ha^{-1}) because it was harvested before plots and treatments were established. The growing conditions in 2010 were the most favorable of the three seasons. Forage biomass in 2011 was reduced by cool spring temperatures and low summer rainfall (Table 1). Urea had the highest yield in 2009, (Table 6). In 2010, urea and digested broadcast slurry had higher yield than the digested slurry applied subsurface. Slurry type and application method did not affect yield in 2009 or 2011.

Similar trends occurred when comparing crop N uptake in the forage grasses (Table 6). Urea-treated plots accumulated the most plant N, ranging from 296 to 655 kg N ha^{-1} removed per year. Uptake of N in forage grasses was greatest in 2010 (Table 6). Slurry type and application method did not have a significant effect on N uptake any year.

Table 5: Soil pH, Bray-P, and exchangeable K at start of experiment and after two years of slurry applications.

Plot	pH	Bray P	NH_4OAc K
		mg kg^{-1}	
Baseline, 12 May 2009			
Control	6.0	173	591
Urea	6.0	176	608
Raw-subsurface	6.0	160	598
Raw-broadcast	6.0	165	632
Digested-subsurface	6.1	140	616
Digested-broadcast	6.0	168	612
2 December 2010			
Control	6.2a	173	379b
Urea	6.0b	176	286c
Raw-subsurface	6.3a	186	479a
Raw-broadcast	6.2a	185	465a
Digested-subsurface	6.2a	173	447ab
Digested-broadcast	6.2a	162	440ab

Letters in a column within a year indicate significant differences at $\rho = 0.05$, letters are not included when no significant differences were found. Samples from different dates were analyzed separately using an ANOVA.

Table 6: Annual forage yield and N uptake, 2009 to 2011.

Treatment	Forage yield Dry Mg ha^{-1}			Nitrogen uptake N kg ha^{-1}		
	2009[a]	2010	2011	2009[b]	2010	2011
Control	8.0^{b}	14.1^{c}	9.2^{b}	283^{c}	362^{cd}	192^{c}
Urea	9.5^{a}	18.0^{a}	11.1^{a}	389^{a}	655^{a}	296^{a}
Raw- subsurface	8.6^{b}	16.6^{ab}	10.5^{a}	330^{b}	507^{b}	263^{b}
Raw- broadcast	7.9^{b}	17.0^{ab}	10.8^{a}	308^{bc}	531^{b}	254^{b}
Digested-subsurface	8.6^{b}	16.1^{b}	10.9^{a}	332^{b}	501^{b}	239^{b}
Digested-broadcast	8.7^{b}	17.8^{a}	10.9^{a}	338^{b}	550^{ab}	255^{b}

Letters within a column indicate significant differences at $\rho = 0.05$.
[a]Values for forage yield from the first harvest prior to implementation of nitrogen fertilizer treatments and application method were 7.7 Mg ha^{-1}.
[b]The N content in forage yield from the first harvest prior to implementation of nitrogen fertilizer treatments and application method was 253 kg N ha^{-1}.

Nitrogen uptake was lowest in 2011, likely a result of lower N application rates (Table 4) and poorer weather during the spring and summer. Forages in 2011 also contained significant amounts of clover, an N fixer (27% of the dry mass of forage yield at harvest 1 and 34% at harvest 2). Less than 10% of the forage biomass was clover in 2009 and 2010.

In the first full season of the study (2010), the recovery of applied N in the forage (ANR) was higher than in 2011 (Table 7). More favorable weather patterns for growth in 2010 compared with 2011 probably increased ANR in 2010. Urea treatments had an ANR of 65% in 2010 and 31% in 2011. Calculations based on total N applied in slurries were lower, ranging from 29 to 40% in 2010 and 15 to 24% in 2011, and similar between the two types of slurry. ANR calculations based only on the amount of total NH_4^+–N applied in slurries were 52 to 70% in 2010 and 35 to 53% in 2011, similar to ANR observed for urea.

3.3. Soil Nitrate-N. Plots receiving urea had the highest concentration of soil nitrate-N over the three seasons, while there were few differences among the slurry treatments (Table 8). Soil nitrate-N concentrations were highest in all fertilized treatments from July to the start of the fall rainy season, when the potential for leaching increases. Soil nitrate-N levels were greatest in 2009, likely because of the high rates of N applied that year. Lower soil nitrate-N in 2010 reflected the high N uptake during the favorable growing conditions that year. Soil nitrate-N increased again in 2011, particularly in the fall. This was despite a lower N application rate and may reflect the reduced yield and N uptake by the forages during the less favorable growing season in 2011.

3.4. Microbial Groups. Microbial groups in general did not vary with treatment, but rather varied by year (Table 9). The control and urea treatments varied from the other treatments most consistently for most groups, while no consistent differences were observed among the slurry treatments. By 2011, the control treatment had significantly lower bacteria and anaerobic markers than the other treatments, but similar levels of overall microbial biomass and fungi.

Table 7: Apparent nitrogen recovery (ANR) in harvested forage as percentage of total and ammonium N applied, 2010 and 2011.

	ANR 2010		ANR 2011	
Treatment	% of Total N	% of NH_4^+–N	% of Total N	% of NH_4^+–N
Urea	65	65	31	31
Raw-subsurface	29	60	15	35
Raw-broadcast	34	70	24	47
Digested-subsurface	30	52	23	53
Digested-broadcast	40	70	20	46

Urea fertilizer considered equal to NH_4^+ in plant availability.

Table 8: Soil NO_3^-–N (mg kg^{-1}) at 0 to 30 cm depth, 2009–2011.

	Soil NO_3^-–N (mg kg^{-1}) Treatment					
Sample Date	Control	Urea	Raw subsurface	Raw broadcast	Digested subsurface	Digested broadcast
2009						
12-May	20gh	21gh	18gh	19gh	19gh	20gh
4-Jun	18gh	28fg	24fg	23 g	30fg	24fg
6-Jul	35fe	80b	71bc	76bc	68c	65cd
3-Aug	34f	86ab	80b	76bc	86ab	71bc
9-Sep	20gh	91a	66cd	82ab	72bc	67c
21-Sep	20gh	81b	53de	62cd	78bc	55d
1-Oct	17gh	62cd	52de	50de	56d	45de
19-Oct	14gh	91a	35fe	54de	44e	45de
3-Nov	11h	54de	23g	30fg	29fg	23g
19-Nov	10h	22gh	9.8h	12h	11h	10h
30-Nov	11h	11gh	12h	12h	10h	12h
2010						
26-Feb	12fg	11fg	15ef	15ef	13f	14ef
11-May	13f	23d	20de	20de	20de	18ef
16-Jun	6.1g	9.2fg	7.9g	7.0g	7.4g	7.3g
13-Jul	10fg	25cd	18e	18de	16ef	14ef
17-Aug	13fg	61a	23cd	22de	18ef	22de
30-Sep	18de	36b	23cd	28c	22de	19de
12-Oct	12fg	28bc	22de	22de	27cd	24cd
26-Oct	7.2g	12fg	15ef	17ef	21de	16ef
2-Dec	6.9g	8.2g	11fg	9.5fg	10fg	10fg
2011						
4-Apr	6.1g	6.2g	7.0g	6.5g	7.0g	8.0g
21-Jun	7.9g	18ef	11fg	11fg	12fe	12fg
4-Aug	8.7g	21ef	15fg	17ef	18ef	18ef
30-Aug	12fg	43cd	22ef	16f	23ef	17ef
16-Sept	17ef	48bc	39cd	48bc	48bc	32d
29-Sept	17ef	46c	36d	42cd	55b	36d
13-Oct	19ef	66a	45c	44c	50bc	44c
4-Nov	8.4g	32d	28de	24e	30de	23ef

Letters within a year indicate significant differences at $\rho = 0.05$.

4. Discussion

4.1. Forage Biomass, N Uptake and ANR. Forage biomass, plant N-uptake, and nitrate concentrations during the 2009–2011 growing seasons were affected by seasonal and long-term N management (a history of manure applications) that resulted in high N uptake from the control treatments. Also, favorable growing conditions in 2010 allowed for a more productive field season in this year. For this study, total harvest yield during each season was within the range of other published work where animal manures were applied to forages harvested multiple times over a season [16, 17, 41].

While other studies have shown incorporation of manure to increase yield and crop N content by reducing gaseous losses [13], we did not see an improvement in crop N content from incorporation of slurries in this system. Forages grown

Table 9: Soil microbial analyses from field plots in the spring, 2009–2011.

	Biomass g kg^{-1}	Bacteria Mole percent[a]	Fungi Mole percent	Bacteria to fungi ratio	Anaerobe Mole percent	Mono-unsaturated Mole percent
May 2009						
Control	535 ab	0.246	0.098	3.01	0.091	0.338
Urea	433 c	0.246	0.092	3.23	0.092	0.348
Raw-B	538 ab	0.243	0.093	3.18	0.094	0.335
Raw-SSD	454 bc	0.237	0.094	3.07	0.091	0.330
Digested-B	473 bc	0.242	0.092	3.18	0.093	0.324
Digested-SSD	623 a	0.238	0.083	3.45	0.091	0.322
May 2010						
Control	610 a	0.243 b	0.071 abc	4.18 ab	0.115 ab	0.328 b
Urea	333 b	0.215 c	0.074 ab	3.48 c	0.101 b	0.322 b
Raw-B	401 a	0.266 ab	0.084 a	4.04 bc	0.116 ab	0.357 ab
Raw-SSD	297 b	0.268 a	0.066 bc	4.91 a	0.127 a	0.414 a
Digested-B	258 b	0.259 ab	0.071 abc	4.65 ab	0.123 a	0.398 a
Digested-SSD	279 b	0.267 ab	0.066 c	4.97 a	0.125 a	0.406 a
April 2011						
Control	512	0.221 b	0.087 ab	3.11 d	0.082 c	0.341 b
Urea	447	0.250 a	0.078 c	3.96 a	0.094 ab	0.380 a
Raw-B	489	0.257 a	0.093 ab	3.35 bcd	0.092 b	0.335 b
Raw-SSD	428	0.253 a	0.095 a	3.25 cd	0.100 ab	0.345 b
Digested-B	441	0.258 a	0.085 bc	3.68 ab	0.101 ab	0.357 ab
Digested-SSD	491	0.255 a	0.085bc	3.61 abc	0.102 a	0.359 ab

Letters within a column within a year indicate significant differences at $\rho = 0.05$. No letters indicate no significant differences within that column.
[a]Mole percent = (mole substance in a mixture)/(mole mixture) %.

in plots with broadcast applied slurries took up the same amount of N or more N than with subsurface deposition, which may have been caused by plant-growth disturbance from the airway banderator when subsurface applying effluent. Additionally, the infiltration rate of the anaerobically digested slurry may have been rapid enough that gaseous losses in the field were not different among subsurface deposition and broadcast applications. From an agronomic perspective, the two slurry types performed equally well as urea over the three growing seasons. Anaerobically digested slurry was suitable for forage production when applied at rates equal to raw dairy slurry. Moller and Stinner [8] also reported no differences in N uptake between digested and undigested slurry. How the system will respond after many years of anaerobically digested slurry application is unclear as the quantity of organic N applied is less than that of raw dairy slurry, supplying less recalcitrant N to the pool of soil organic matter.

4.2. Soil Nitrate-N and Microbial Groups. We found few differences between slurry treatments in seasonal soil NO_3^- concentrations. There was, however, significantly more nitrate-N in urea-treated plots on many dates, even though there was slightly less total N applied to the urea plots in some years. The spike in nitrate concentration in October on soils where urea was applied in place of slurries indicates a greater potential for N leaching from urea compared with the slurries. All treatments declined in NO_3^- concentrations to levels that were not significantly different from control treatments after the fall rains began. Lower soil nitrate-N during the growing season of 2010 compared with 2009 may be due in part to a lower amount of total nitrogen applied. Also, little rainfall during the 2009 growing season may have caused a buildup of soil nitrate in the surface layers. Higher late-season nitrate in 2011 compared with 2010 may have been the result of poorer growing conditions reducing N uptake.

Postharvest soil nitrate-N is a measure of residual plant-available N subject to leaching loss, and an indicator of excess applied N and/or poor yield. The recommended timing of postharvest soil nitrate testing in forage systems that utilize animal manure as a source of fertility in the Maritime Pacific Northwest is prior to October 15 [34]. Nitrate concentrations from soil samples collected from our site in mid-October showed that all treatments except the control exceeded 30 mg NO_3–N kg ha^{-1} in 2009 and 2011, with NO_3–N levels highest in the urea treatment. Fall nitrate-N levels above 30 mg kg^{-1} are considered excessive in manured pastures, and reduced rates and adjusted timing of applications are recommended [34].

While soil nitrate concentrations decreased during the fall 2009 months, it is likely that some of this nitrate was not entirely leached from the system, but stored in the canary grass rhizomes over winter as described by Partala et al. [18].

This is evident in the significantly higher yields and nitrogen content of forages during the early season harvest on 26 April 2010.

While the focus of this study is N, dairy manure also contains high levels of P. Runoff from high-P soils can lead to eutrophication in fresh water. Soil P levels were already excessive at the start of this study, because of the history of dairy manure applications at the site, and P tended to increase in the slurry-treated plots during the study (Table 5). The anaerobically digested slurry contained less P than the raw dairy slurry, probably because it had a lower solids content, which would lead to less P accumulation over time.

Microbial groups varied with year more than treatment in these field studies. Urea treatments varied from the other treatments to the greatest extent. The raw and anaerobically digested materials did not alter the soil microbial components as determined by PLFA. Our results may partially be the result of past manure applications.

5. Conclusions

Subsurface deposition did not increase yield or N uptake compared with surface broadcast application, possibly because the slurries were low enough in solids to infiltrate readily into the soil, and because the subsurface injectors could have disrupted plant growth. Anaerobically digested dairy slurry was shown to provide adequate soil fertility and N availability for crop uptake and forage production over the three field seasons. In the short term, anaerobically digested slurry did not significantly increase yield or N uptake compared with similar rates of raw slurry.

This study indicated that soil nitrates measured to a 30 cm depth were fairly consistent across slurry treatments and application methods during each of the field seasons. Soil nitrate-N was lower in 2010 due to favorable growing conditions and lower total applied N relative to 2009. Although urea treatments had the highest apparent N recovery value, the potential for nitrate leaching was also greatest under this management. Anaerobically digested slurry did not increase soil NO_3^- concentrations or alter the microbial composition and provided equal forage production and similar N use efficiency when compared to undigested dairy slurry.

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