ANAEROBIC DIGESTERS CHANGE THE PHOSPHORUS LEACHING BEHAVIOR OF DAIRY MANURE

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Master of Science

by
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ABSTRACT

This study analyzed how anaerobic digestion of dairy manure might change the amount, form, and rate of phosphorus (P) leached by rainfall. Anaerobic digestion has become an increasingly popular manure management option because it generates methane that can be used to make energy, but little is known about the behavior of P when digested manure is applied to fields. Leaching experiments were performed using simulated rainfall on digester influent (undigested manure) and effluent (digested manure) collected from a dairy farm near Ithaca, NY. A previously published manure-P model was applied to the experimental data to quantify rates of P leaching. Dissolved P-leaching from digested and undigested manures were similar to each other, although digested manures appear to generally leach more dissolved P. Interestingly, both digester influent and effluent leached dissolved P more rapidly and in greater quantities than fresh manure, i.e., manure from a dairy barn floor. It is suggested that the key difference between the liquid manures in this study and "fresh manure" is that fresh manure has a higher solids content, i.e., it is less liquid than the manure used in anaerobic digesters. The findings of this study suggest that it is important to avoid field spreading of liquid manures when rainfall is imminent or fields are wet in order to prevent nonpoint P loading to streams and lakes.

BIOGRAPHICAL SKETCH

Rebecca Marjerison was born in Western Montana and spent her childhood exploring the forests of Montana, Idaho, Northern California, and Southeast Alaska. Her interest in the natural sciences began early, and by the age of ten she had decided she wanted do science for a living. Rebecca was fortunate to have supportive parents and teachers who introduced her to many disciplines and encouraged her to continue her education beyond high school. She began her undergraduate career at Drake University in Des Moines, Iowa in 1993. She left after a year and worked at various jobs until the birth of her son in 1997. After dedicating a few years to rearing this little scientist, Rebecca returned to undergraduate studies at the University of Alaska Southeast in Juneau, Alaska. She graduated with a Bachelor of Science in Environmental Science in 2003. Shortly thereafter she was employed by the State of Alaska in the pollution response program. The work, including a month of shoreline assessment after an oil spill in the Aleutian Islands, was interesting and fulfilling. Still, Rebecca felt her education was not complete, and in 2007 she began her pursuit of a graduate degree at Cornell University. She intends to continue on this path until she receives her doctorate degree, fulfilling the goal she set for herself in the fifth grade.

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CHAPTER 1

INTRODUCTION

Although animal manure has traditionally been perceived as an important fertilizer resource, the increase in the size of dairy farms and other livestock operations relative to the amount of land available for manure application has made manure management a waste problem (e.g., Ribaudo et al., 2003). This concern is likely to grow as large confined animal feeding operations (CAFOs) become increasingly commonplace (USEPA, 2003; Centner, 2006). Animal manure is generally rich in phosphorus (P) and P accumulation on farmed soils throughout many parts of the U.S. has elevated agricultural soil P levels to the point where they commonly exceed crop needs (NRC, 1993; Sharpley et al., 1998). More critically, P that washes off agricultural land into streams and other fresh water bodies has been identified as a serious water quality issue that often contributes to fresh water eutrophication and associated problems (Carpenter et al., 1998; Sharpley et al., 2000; USEPA, 2002).

While livestock agriculture grapples with ways to protect water quality, it is also desirable to protect air quality (e.g., NRC, 2003; Konewaran and Nierenberg, 2008) and find sustainable energy sources (e.g., Champagne, 2007; Cuellar and Webber, 2008). Anaerobic digestion of animal manure is an attractive management option because it reduces odors and manure-borne pathogens, and can be used to generate heat and electricity for use on the farm (e.g., Tikalsky and Mullins, 2007) or by those wishing to purchase power from renewable energy sources. Since 2000, the number of on-farm anaerobic digesters in the U.S. has increased from about 50 to over 110 (USEPA, 2007). The general principle of anaerobic digestion is that manure is kept in an anaerobic environment (digester) for a retention time of approximately 20 days.

During this time, bacteria consume some of the organic matter in the manure and produce “biogas,” primarily composed of methane, which is then burned to produce energy. While there is evidence that anaerobic digestion may help alleviate some of the environmental concerns associated with animal agriculture, there is little research on the potential influences of this practice on P mobility in manure.

Even without the added complexity of anaerobic digestion, controlling nonpoint sources (NPS) of P has proven vexing. Many so-called Best Management Practices (BMPs) designed to reduce P loads to streams work inconsistently, at best (e.g., US Army Corps of Engineers, 1991; Lowrance et al., 1997). Indeed, several BMPs actually have been shown to enhance P loads to streams (Dillaha et al., 1988; 1989a; 1989b; Gaynor and Findlay, 1995; Daverede et al., 2003; Novotny, 2003). One source of complication is the wide variability in total P and bioavailable P constituents among manure types and treatments. Some of the factors that influence P content and form (or species) in livestock manure include the type of animal, the animals' diets and nutrition, and manure handling methods (Sharpley and Moyer, 2000; Dou et al., 2002; Toor et al., 2005). Composted manure, for example, has been found to leach a lower proportion of its total P than fresh manure but slightly more bioavailable P (Sharpley and Moyer, 2000). Like composting, anaerobic digestion appears to change the composition of P released from manure (e.g., Gungor and Karthikeyan, 2005), but there has been very little research on the effects of anaerobic digestion on the leaching behavior of P from manure. This information is important to developing strategies for applying digested manure to fields that will minimize risks of P from NPS pollution.

In a study of Wisconsin dairy farms, Gungor and Karthikeyan (2008) found that water-extractable P (WEP) made up 45% to 70% of the total P in undigested manure, but only 25% to 45% of the total P in digested manure. Gooch et al. (2007) collected samples from dairy farms around New York State and found that orthophosphate concentrations were generally higher in digester effluent than influent. Their data show orthophosphate making up 48% to 61% of total P in undigested and 52% to 74% in digested manure. The reasons for these differences are not entirely clear, but researchers have shown that mineralization (Gungor and Karthikeyan, 2008), microbial activity, operating temperature, and pH (Sanchez et al., 2000), all play various and probably interacting roles.

Although knowing the changes in P composition associated with anaerobic digestion is important, from a water quality perspective it is perhaps more important to know if digestion changes the amount of dissolved P that will leach from the manure, and how rapidly it will be released during storm events. Gerard-Marchant et al. (2005), using data from Sharpley and Moyer (2000), and Muck (1978), demonstrated that P release during rainfall, for a wide variety of manures and associated composts, could be characterized by second order reaction kinetics, i.e. the reaction rate is proportional to the square of the concentration of leachable P in the manure. The equation describing the cumulative release of P from manure during rainfall was found to be (Gerard-Marchant et al. 2005):

$$M(t) = M_0 \frac{t}{t + \tau} \qquad (1)$$

Where $M(t)$ is the cumulative dissolved P released, M_0 is the initial amount of potentially leachable P in the manure, and τ is a time or rate parameter that describes how rapidly P is leached; τ is the characteristic time, a sort of “half-life” of the available P. Gerard-Marchant et al. (2005) showed how these parameters could be determined with simulated rainfall experiments and that the experimentally fitted M_0 agreed well with directly measured amounts of WEP from the initial manure; see Sharpley and Moyer (2000) for details about measuring WEP. Equation (1) has been successfully used to describe leaching from many animal manures and composts (Gerard-Marchant et al. 2005) and in several watershed-scale modeling studies (Hively et al., 2006; Easton et al., 2008; 2009) in which M_0 was determined directly from on-farm manure samples and τ was taken from Gerard-Marchant et al. (2005).

This study is essentially an addendum to the earlier work by Gerard-Marchant et al. (2005) and Sharpley and Moyer (2000); these two studies considered a wide range of animal manures and associated composts but did not include manure from anaerobic digesters. To fill this gap, we ran rainfall simulations similar to those of Sharpley and Moyer (2000) on digester influent and effluent and measured the leached P. The rate constant, τ, was determined following the protocol of Gerard-Marchant et al. (2005) by fitting Eq. 1 to the leached P data from the rainfall experiments. Because P contents vary substantially, even for a single farm, we used a large dataset of published orthophosphate in pre- and post-digested manure (Gooch et al., 2007) to represent M_0.

CHAPTER 2

METHODS

Manure Collection

Undigested manure (influent) and digester effluent were collected from a 600-cow dairy farm in Central New York. The farm operates a plug-flow anaerobic digester. Each day, about 60 m^3 (11,000 gallons) of manure is pumped from a storage tank into the digester. The new manure pushes the older material through the system and digested manure is pushed out at the opposite end of the digester. The digester's hydraulic retention time is about 37 days (Gooch et al., 2007). Samples were collected on two dates, July 6, 2007 and October 23, 2007. Undigested manure was collected from the storage tank and digested manure was collected from the outflow of the digester. Moisture content of the two manures was measured by weighing samples before and after oven-drying overnight at 110º C. Manure was stored at 4º C before initiating rainfall experiments and analyzing for manure chemical composition.

Rainfall Simulations

To approximate leaching of field-spread manure during storms, we used simulated rainfall events on manure samples in the lab. Rainfall simulation experiments were designed after Sharpley and Moyer (2000) in order to compare our results to theirs. A plastic grate covered with a filter was placed in the bottom of each of six plastic columns (15 cm diameter X 10 cm tall). Twenty grams of wet manure were spread on the filter in each column; three received digested manure and three received undigested manure. Rain was produced using a custom-built rainfall simulator comprised of an oscillating rod with hollow needles attached. The needles were spaced about 10 cm apart. Water was pumped to the needles through plastic tubing using a peristaltic pump. The rainmaker was set to produce a rain rate of 7 cm hr^{-1} and had a uniformity coefficient of 85% (see Walter et al., 2001 for a full description of the rainfall simulator). Rainfall events lasting 30 minutes each were simulated once a day for five consecutive days. Leachate from each column was collected in 1 L HDPE bottles for each rainfall event. Subsamples of leachate were immediately filtered through 0.45 μm filters and refrigerated until chemical analyses could be run.

Dissolved reactive P (DRP) in the leachate samples was measured with a colorimetric method using an OI Analytical FS-3000 analyzer (EPA Method 365.1). Total P of the manure was measured after persulfate digestion, following the method of Greaves et al. (2002). Briefly, oven-dried samples of undigested and digested manure were ground to pass through 0.7 mm sieve; 50 mg of each dried sample was placed in a 150 mL Erlenmeyer flask. Then 0.3 g ammonium persulfate, 40 mL distilled water, and 2 mL 0.5M sulfuric acid were added. The tops of the flasks were covered with aluminum foil. The samples were placed in an autoclave at 15 psi and 121° C for 90 min. After autoclaving, the flasks were allowed to cool and the liquid was filtered through 0.45 μm filters. Samples were refrigerated (4 °C) and later analyzed for P colorimetrically.

Leaching model

The model parameters M_0 and τ were determined by fitting Eq. 1 to cumulative experimental concentrations of DRP in the leachate as per Gerard-Marchant et al. (2005); the model was fit using Microsoft Excel to each column's leachate DRP individually. Representative parameter values were determined by fitting curves through the average measured values for each manure type. Best-fit values for M_0 were compared to measured data.

CHAPTER 3

RESULTS

During the first simulated rainfall, 89% and 93% of the dissolved P leached out of the digested and undigested manure, respectively (Figure 1). Digested manure released more P per dry mass of manure, but had a significantly ($p < 0.1$) longer average characteristic time, $\tau = 4.5$ min, than the undigested manure, $\tau = 3.1$ min (Table 1). From Eq. 1, τ is the time it takes for half of M_0 to leach. The M_0 values for the digested and undigested manure were 3917 mg kg^{-1} and 2806 mg kg^{-1} (Table 1), respectively. As noted earlier, Gerard-Marchant et al. (2005) showed that M_0 is essentially equal to the WEP in the manure.

Table 1. Selected properties of dairy manure used in this study as compared to Sharpley and Moyer (2000) values for fresh and composted dairy manure. Total P and DRP in mg kg^{-1} dry weight equivalent.

Parameter	This study Digested	This study Undigested	Sharpley and Moyer 2000 Fresh	Sharpley and Moyer 2000 Compost
Solid Content (%)				
Mean	6.7	13	30	39
Range	5.8 – 7.3	11 – 15	26 – 35	33 – 49
Total P (mg kg^{-1})				
Mean	8322[a]	7233[a]	3490	16250
Range	6927 – 9583	5150 – 9289	1500 – 7800	8400 – 19900
Water Extractable P inorganic (M_0) (mg kg^{-1})				
Mean	3917[b]	2806[b]	2030	2410
Range	3232 – 4468	2196 – 3428	N/A	N/A
Time Parameter, τ (min.)				
Mean	4.5	3.1	20	65
Range	1.1 - 5.4	2.6 - 6.6	N/A	N/A

[a] Not significantly different

[b] Model fitted M_0 values – instrument problems precluded measuring WEP directly.

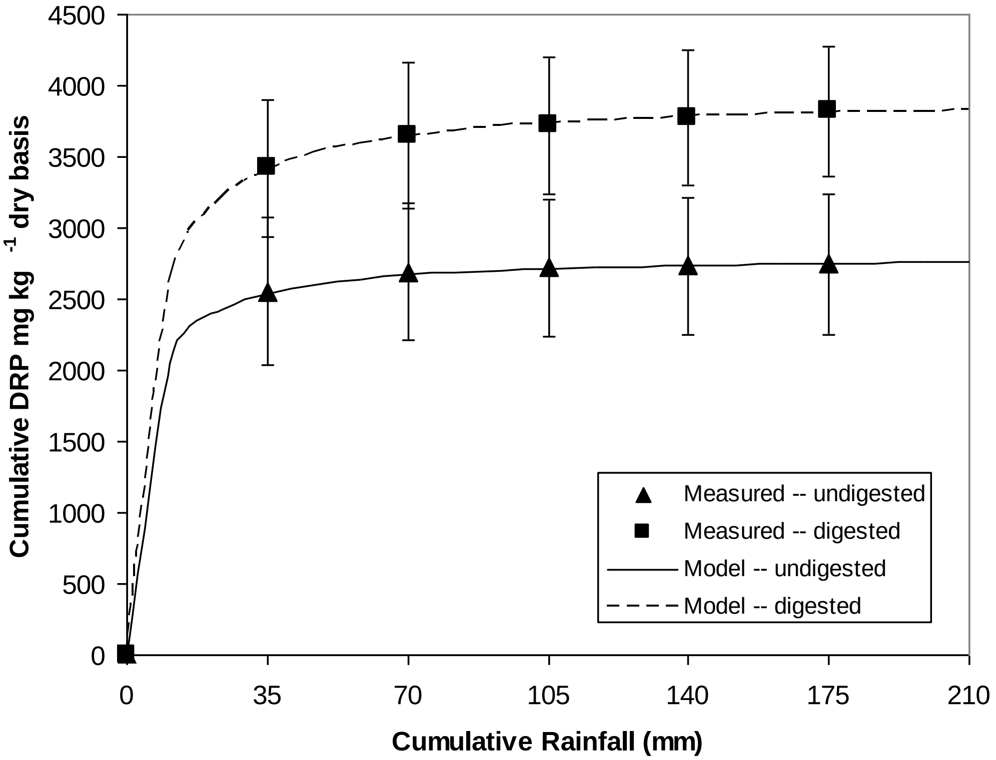

Figure 1. Cumulative release of dissolved reactive P from manures with cumulative rainfall (based on five 30-minute events). Symbols are measured cumulative DRP released during simulated rainfall events. Curves are modeled cumulative DRP released using Equation 1. Dashed line is digested manure, solid line is undigested manure. Error bars are one standard deviation of samples.

Our analysis is much more sensitive to M_0 than τ. The range of τ values determined from our experiments resulted in deviations between the model and average cumulative P leached of about 1% whereas the range of M_0 resulted in deviations greater than 20%. Because the sensitivity to M_0 and the fact that our estimates were based on only two sampling dates, we used data collected by Gooch et al. (2007), who sampled the same farm we used 34 times (monthly from May, 2001 to June, 2002 and from July, 2003 to April, 2005) to estimate a more representative average M_0.

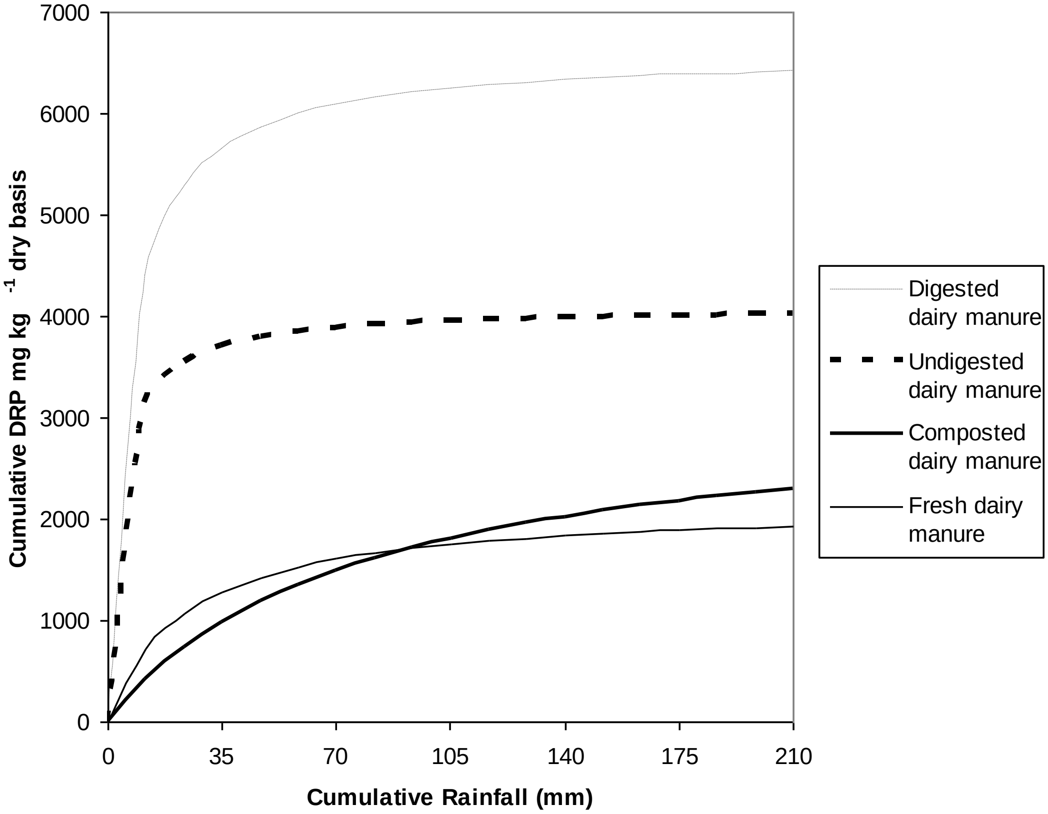

Figure 2. Cumulative release of dissolved reactive P from manures: composted dairy manure (bold-solid line); fresh dairy manure (thin-solid line), undigested manure (bold-dashed line), and digested manure (thin-dashed line). Composted and fresh dairy manure are based on Sharpley and Moyer (2000) and Gerard-Marchant et al. (2005).

Table 2. Selected published fresh or undigested dairy manure properties compared to manure used in this study. Total P and WEP in mg kg^{-1} dry manure.

	This study Undigested	Gooch et al. 2007 Undigested	Sharpley and Moyer 2000 fresh	Chapuis-Lardy 2004	He et al. 2004	Vadas 2006	Dou et al. 2002
Manure Type[a]	tank	tank	fresh	fresh	varied	tank	fresh
Dry Matter (%)							
Mean	13	11	30	15	12	8	N/A
Range	11 – 15	7 – 14	26 – 35	13 - 21	4 – 23	N/A	N/A
Total P (mg kg^{-1})							
Mean	7233	7202	3490	9200	9130	7557	N/A
Range	5150 – 9289	N/A	1500 – 7800	5800 - 12800	4100 - 18300	N/A	4880 - 12650
Water Extractable P inorganic (mg kg^{-1})							
Mean	2806[b]	4099	2030	3790	N/A	2714	N/A
Range	2196 – 3428	N/A	N/A	2250 - 6350	1000 - 6800	N/A	1480 - 6280

[a] Fresh indicates manure collected directly from cow or barn floor. Tank indicates manure collected from storage tank.

[b] Model fitted M_0 value – instrument problems precluded measuring water extracted DRP directly in this study.

Gooch et al. (2007) used a water extraction technique to measure DRP in influent (undigested) and effluent (digested) manure. Although their protocol was slightly different than that of Sharpley and Moyer (2000), for dairy manure it appears that WEP is primarily composed of the constituents that are associated with DRP, i.e., dairy manure WEP is mostly inorganic P and a small amount of organic P (Sharpley and Moyer, 2000). The average DRP determined by Gooch et al. (2007) was substantially higher than our average M_0, although our range of M_0 values fell well within the range of their data (Table 3). The DRP (M_0) values for digested and undigested manures were significantly different from each other ($p < 0.1$) for both Gooch et al. (2007) and our leaching experiments. Using the Gooch et al. (2007) DRP for M_0 and the τ values from our experiment, the expected average DRP release curves for digested and undigested dairy manure are shown in figure 2. Gooch et al. (2007) reported their DRP values on a wet basis, so those values were converted to dry basis for comparison using the reported total solids.

CHAPTER 4

DISCUSSION

Although there are very few published works on P contents in manure specifically associated with anaerobic digesters, our WEP contents in both undigested and digested manures were comparable with the manures analyzed by Gungor and Karthikeyan (2008) using six dairy farms in Wisconsin, as well as manures from the five New York farms analyzed by Gooch et al. (2007). Both of these studies reported their results as mass concentration on a wet-basis, so it is difficult to compare their results to the studies in table 2. We converted our measurements to a wet-basis for comparison (Table 3). As is typical with dairy manure, there was substantial variability in manure P contents, although all three studies have a similar range of values. Interestingly, Gungor and Karthikeyan (2008) report a generally decreasing WEP content when dairy manure was digested whereas Gooch et al (2007) observed increasing WEP concentration (Table 3). Our manure samples showed a decrease in WEP on a wet-basis (Table 3) but an increase in WEP on a dry-basis (Table 1). The reasons for these differences are probably related to changes in the solid forms of P during anaerobic digestion (Gungor and Karthikeyan, 2008). There is some change in concentration associated with the fact that digestion removes some of the manure mass to produce biogas. However, in our study, total P, which should be conserved, increases in concentration (dry basis) by 10 to 15% (not significant, p-value <0.1) whereas dissolved P increases by 40 to 50%, indicating that some chemical transformations are contributing to higher DRP concentrations.

The total P and WEP in the undigested manure in this study are generally comparable to total P and WEP in dairy manure reported in other studies (Table 2). The exception is the manure studied by Sharpley and Moyer (2000), which had substantially lower total P and somewhat lower WEP than ours. Their mean values were lower than all the other studies shown in table 2 as well. The other unique aspect of the Sharpley and Moyer (2000) data was the relatively high dry matter content. Other researchers have noted that decreased dry matter content corresponds to increased total P and WEP (He et al., 2004; Kleinman et al., 2002; Vadas and Kleinman, 2006). This may explain the discrepancy between Sharpley and Moyer's (2000) results and the other studies in table 2.

Table 3. Selected properties of undigested and digested dairy manure. Total P and WEP (inorganic) in mg kg^{-1} wet manure.

	This study Digested	This study Undigested	Gooch et al. 2007 Digested	Gooch et al. 2007 Undigested	Gungor and Karthikeyan 2008 Digested	Gungor and Karthikeyan 2008 Undigested
Number of samples	2	2	237	215	11	11
Solids Content (%)						
mean	6.7	13	6.6	9.5	5.8	9.8
range	5.8 – 7.3	11 – 15	4.0 – 8.5[b]	5.0 – 15.5[b]	4 – 8	8.5 – 12.5
Total P (mg kg^{-1})						
mean	559	760	581	596	604	676
range	408 - 706	714 – 817	487 – 811[b]	503 – 803[b]	380 - 850	420 - 850
Water extractable P (inorganic) (mg kg^{-1})						
mean	276[a]	350[a]	364	331	209[c]	346[c]
range	233 - 308	301 – 394	290 – 534[b]	242 – 457[b]	149 - 311[c]	248 - 360[c]

[a] Model fitted M_0 value – instrument problems precluded measuring water extractable P directly in this study.

[b] Ranges for each dairy were not reported so these are ranges of means.

[c] Calculated from total P and percent of TP as WEP.

To put the leaching behavior of digested and undigested dairy manure in context, we compared our results with modeled results based on Sharpley and Moyer's (2000) DRP observations for fresh and composted dairy manure (Figure 2). It is important to note that "fresh" manure is not the same as the digester influent (referred to here as undigested manure) used in this study. Sharpley and Moyer (2000) used manure scraped directly off a barn floor. The digester influent, i.e., undigested manure, in this study was taken from a storage tank where it had been mixed with water and possibly other liquid wastes to facilitate pumping through the digester system, resulting in lower solid content. Table 1 summarizes the WEP (= M_0) and τ values for this experiment Sharpley and Moyer's (2000) experiments.

Although this study was designed to compare leachable P from digested and undigested dairy manure, it was perhaps more interesting that both the undigested and digested manure in this study leached much faster and released more DRP than fresh manure (Figure 2); note that although the differences in leaching half-life (τ) was significantly (p-value < 0.1) different between undigested and digested manures, the difference was on the order of a minute, which is unlikely to be significant in a management context. The rapid leaching seen in this study is likely due to the very low total solids content (percent dry matter) of the anaerobic digester manures, both undigested and digested, relative to fresh and composted dairy manures (Table 2). The potential for rapid leaching of P from digester-associated manures (and probably any liquid manure system) suggests that field spreading should avoid imminent rain or, perhaps, wet field conditions. Future work might focus on differences in P-leaching risks between liquid and more solid manure handling practices.

The high water content of the liquid manure could increase not only DRP, but also runoff risks. As an example, a typical manure application rate in New York, based on desired nitrogen application, is 65,000 to 75,000 L ha^{-1} (Karl Czymmek, Cornell Animal Science Dept, Pers. Comm.), although this volumetric application rate is generally lower for manures with high solids content and higher for very dilute (low solids content) manures. Assuming a simple, average rate, spreading manure would result in a spatial application rate of about 35 kg DRP ha^{-1} (37 and 32 kg-DRP ha^{-1} for digested and undigested manures, respectively, based on data from Gooch et al., 2007). This average rate also results in approximately 0.63 cm of water (0.64 and 0.62 cm of water for digested and undigested manure, respectively). During the spring and fall, when access to fields for manure spreading is most commonly available, the soils are typically near field capacity so this extra water might be critical in triggering a leaching event. The combination of rapid DRP leaching rate and high water content in manure might heighten water quality risks.

CHAPTER 5

CONCLUSIONS

Unsurprisingly, we found that dairy manure that has been through an anaerobic digester has lower total solids content than undigested manure. There was no significant difference in the amount of total P per dry mass of digested manure compared to undigested manure. Digested manure leaches more DRP but does so slightly more slowly than undigested manure during simulated rainfall.

Comparing these results to fresh dairy manure (manure scraped off a barn floor) in a previous study, we found that both influent to and effluent from the digester have lower solids content, leach more DRP and leach it much faster than fresh manure. We speculate that the rapid DRP leaching is primarily due to the highly liquid form of the manure (low solids content) rather than from digestion, *per se*. Thus, our findings may be applicable to liquid manure handling systems in general. We also suggest that the high water content of manure managed in this way might increase runoff risks, thus, causing extra concern for water quality. The combination of rapid leaching of reactive P from digested (or liquid) manure and potentially high water applications suggests that manure applications should be targeted to the driest areas in the landscape and at times with low probability of rain.

APPENDIX A

DATA

Table A.1. Total and water extractable P in manures. Total P was measured after persulfate digestion. Water extractable P was measured after 1 h extraction with 25:1 water to wet manure (at least 200:1 water to dry manure).

	Undigested manure		Digested manure	
	Summer 2007	Fall 2007	Summer 2007	Fall 2007
Total P (mg kg^{-1})				
mean	5301	9165	7327	9318
stdev	212	176	566	376
n	2	2	2	2
Water Extractable P (mg kg^{-1})				
mean	NA	3005	NA	2851
stdev	NA	1491	NA	188
n	NA	2	NA	2

Table A.2. Dissolved reactive P in simulated rainfall leachate. P concentrations are in mg kg^{-1} dry manure.

	Undigested manure		Digested manure	
	Summer 2007	Fall 2007	Summer 2007	Fall 2007
Rainfall 1				
mean	2101	3006	3786	3056
stdev	225	64	302	303
n	3	3	3	3
Rainfall 2				
mean	172	106	272	186
stdev	27	55	66	101
n	3	3	3	3
Rainfall 3				
mean	31	22	55	95
stdev	4	28	32	26
n	3	3	3	3
Rainfall 4				
mean	14	17	39	68
stdev	3	15	9	41
n	3	3	3	3
Rainfall 5				
mean	4	33	29	109
stdev	4	9	13	2
n	3	2	3	2

APPENDIX B

OTHER EXPERIMENTS AND LESSONS LEARNED

Because the results of the simulated rainfall experiments showed large differences between the amount of P being leached relative to the amounts extracted in a water extraction, we tried to identify potential causes of these differences. Specifically, we investigated the potential roles of time, water-to-manure ratio, and exposure to air during the water extraction process. Kleinman et al. (2002) found that the amount of P extracted increases with the water-to-manure ratio for undigested manure. Extraction time was also studied by Kleinman et al. (2002) who found that manure P is positively correlated with shake time. Few, if any, studies have examined the effects of exposure to air during extraction. This appendix is a brief summary of our preliminary findings regarding these factors.

To study the effects of time, subsamples of manures collected July 6, 2007 were blended for 10 minutes to improve uniformity. Blended manure, equivalent to 0.5 g dry weight, was added to 50 ml centrifuge tubes; six (6) tubes of each manure type (digested and undigested) were used. Thirty (30) ml distilled water was added to each tube. All tubes were placed on a reciprocal shaker. Two tubes of each manure type were removed from the shaker at 30 minutes, 60 minutes, and 16 hours. Tubes were centrifuged for 10 minutes. Supernatants were passed through a 45 μm filter and the samples were refrigerated until analysis. Samples were analyzed for orthophosphate with a colorimetric method using an OI Analytical FS-3000 analyzer (EPA Method 365.1). Sample pH was measured at a 4:1 water to wet manure ratio.

Results of the extraction time test are shown in table B.1. The amount of P extracted increased with extraction time for both undigested and digested manures. Undigested manure showed a stronger response; extracted P from undigested manure increased by about 60% from 30 minutes to 16 hours whereas the increase for digested manure was about 9%. A 1 hour shake time is often used (e.g. Sharpley and Moyer, 2000; Chapuis-Lardy, 2004), even though longer times result in more P released. Kleinman et al. (2002) found that the 1 hour extraction time produced the best correlation between manure WEP and experimental runoff DRP.

Table B.1. Inorganic P in manure extracts with different shake times.

		Undigested manure	Digested manure
		mg kg^{-1} dry basis	
0.5 h			
	mean	2187	484
	stdev	48	12
	n	2	2
1 h			
	mean	2428	507
	stdev	249	1
	n	2	2
16 h			
	mean	3595	528
	stdev	116	15
	n	2	2

The mean pH of the manure samples was 8.34 for digested and 7.89 for undigested manure.

The effects of water-to-manure ratio and exposure to air were studied using blended subsamples of manure collected October 23, 2007. For the high extraction ratio, 1 g of either undigested or digested manure was placed in each of eight (8) 50 ml centrifuge tubes. Then 25 ml distilled water was added to each tube. For the low extraction ratio, 7.5 g undigested or 8.5 g digested manure were used and 30 ml distilled water was added to each tube. The different amounts of different manure types were used to account for differences in percent solids. Half of the tubes were placed without caps on an orbital shaker. The other half were capped and placed on a reciprocal shaker. All tubes were shaken for 1 h and then centrifuged for 10 minutes. Samples were filtered through a 45 μm filter and were refrigerated until analysis.

The higher water-to-manure ratio extracted more P than the lower ratio for both manure types. The closed tube extraction tests had very similar results between undigested and digested manures. For the samples that were open to air during shaking, the digested manure released about 20% more P than the undigested at both extraction ratios. These results are summarized in table B.2.

Table B.2. Inorganic P in manure extracts based on extraction ratio and exposure to air.

			Undigested manure	Digested manure
Closed tube				
	high extraction ratio	mean	3005	2851
		stdev	1491	188
		n	2	2
	low extraction ratio	mean	432	425
		stdev	130	113
		n	2	2
Open tube				
	high extraction ratio	mean	3199	4081
		stdev	1911	431
		n	2	2
	low extraction ratio	mean	450	551
		stdev	24	34
		n	2	2

The differences between the results of the shake time experiment and the main experiment were probably due to differences in extraction ratio. The shake time test was conducted at a ratio of about 60:1 dry basis and the rainfall experiments have a ratio of about 300:1. Also, the shake time test only included manure from the first sample date, and the main results are an average of both sampling dates.

The results for both manure types were consistent with previous findings with respect to changes in extraction time and water-to-manure ratio, although time was less of a factor for digested manure. Further research would be necessary to draw conclusions about the effects of exposure to air on manure P extraction and we have not yet developed a good hypothesis for why open tubes released more P than closed tubes. We believe open-tube extractions probably represent field conditions better than closed-tube extractions. These results suggest that digested manure responds differently than undigested manure to open air extraction. This could be important in understanding P dynamics in the field where “extraction” by rainfall takes place in the presence of air.

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