IMPACT OF ANAEROBIC LAGOON MANAGEMENT ON SLUDGE ACCUMULATION AND NUTRIENT CONTENT FOR DAIRIES

S. Mukhtar, J. L. Ullman, B. W. Auvermann, S. E. Feagley, T. A. Carpenter

ABSTRACT. *The contents of twelve primary dairy lagoon cells under different management practices in three central Texas counties were evaluated for sludge accumulation and physicochemical characteristics. Composite samples were comprised of the wastewater column from the top of the lagoon to the top of the dense sludge layer. The composite samples were thought to represent a slurry mix typical of agitated lagoon material intended for land disposal. Analyses included pH, total solids (TS), volatile solids (VS), total Kjeldahl nitrogen (TKN), total ammonium-nitrogen (NH_4-N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), zinc (Zn), copper (Cu), manganese (Mn), and electrical conductivity (EC).*

Statistically, lagoon management practices and treatment effectiveness in terms of reduced sludge accumulation and nutrient content were not strongly linked. However, some practices appear to influence the physicochemical properties of the slurry mix, including use of fresh flush water, increasing the number of treatment cells, and separation of dry lot runoff. Total Kjeldahl nitrogen, P, and K were linearly correlated to TS, indicating higher nutrient concentrations in the anaerobic lagoon sludge. The resultant elevated nutrient levels in the slurry mix, compared to supernatant values, will require greater land areas to meet P-based regulations. Land applying a lagoon slurry mix will require approximately two and a half times as much land area compared to N-based application rates. Consideration of best management practices (BMPs) may be advised to alleviate lagoon clean-out and sludge disposal challenges.

Keywords. *Anaerobic lagoon, Dairy, Nitrogen, Phosphorus, Sludge, Slurry, Solids.*

Dairy operations in temperate regions of the U.S. predominantly use liquid manure handling systems. This management strategy typically employs the use of anaerobic lagoons to store and treat wastewater originating from production facilities. These structures provide long-term storage to allow field application at appropriate times, require minimal labor and energy inputs, and have low construction and operation costs.

In an anaerobic lagoon, livestock waste is diluted with water, and treatment occurs through biological activity. The total design volume of an anaerobic lagoon encompasses the sum of the sludge, treatment, livestock waste, wastewater, and runoff volumes, as defined by ASAE Standard EP403.2 (*ASAE Standards*, 2002). Sludge volume allows for the accumulation of fixed and nonvolatile solids and other inert portions of the livestock waste stream. The treatment volume is sized based on the waste load of volatile solids and climatic conditions. Livestock waste volume corresponds to the quantity of manure and other solid wastes (e.g., bedding and spilled feed) produced between drawdown events. Wastewater volume represents contaminated water, such as unrecycled flush water and milkhouse wastewater produced between drawdown events. Runoff volume embodies all runoff and precipitation that enters the lagoon, including runoff from open lots routed to the lagoon.

Excessive sludge build-up encroaches on the other volumes comprising the lagoon, rendering treatment of biodegradable material less effective. Consequently, the rate of sludge accumulation increases and creates potential for excessive odors and nutrient accumulation (Bicudo, et al., 1999; Miner et al., 2000). Although the rate of sludge accumulation in lagoons may be minimized by proper lagoon design, partial removal of solids from flushed manure by mechanical separation or gravitational settling, and minimizing feed wastage and spillage, periodic sludge removal is required to restore the minimum treatment volume. Dairy operations in central Texas typically use a two- or three-cell lagoon system for manure and wastewater storage, treatment, and land application of effluent. Manure and wastewater are treated, and most sludge and settleable solids are stored in the first (primary) cell, while effluent, treated and diluted manure from a second or third cell is used to irrigate crops and pastures or recycled for flushing manure alleys. A majority of these systems have been in operation for more than ten years without removal of solids or sludge from primary cells, raising concerns about the excess sludge build-up or nutrient accumulation in the primary anaerobic lagoons.

Although research has established performance of anaerobic lagoons in terms of environmental contaminants, such as chemical oxygen demand (COD), volatile solids (VS), and nutrient recovery (Safley and Westerman, 1992), a literature

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review identified no studies that consider impacts of lagoon operation on sludge accumulation and corresponding lagoon longevity. Furthermore, increasingly rigorous regulations on land disposal of animal wastes, such as the USEPA's CAFO Final Rule (68 FR 7176, February 12, 2003), require investigation of lagoon management practices to determine effective techniques to help meet land area requirements for field application. A shift to P-based land application rates may require some dairies to develop alternatives to current manure handling systems; therefore, lagoon performance has direct implications on meeting regulatory guidelines. For instance, off-site disposal will entail transport costs contingent on waste stream characteristics.

Our objective was to determine the impacts of different operation and management practices on the extent of sludge accumulation and nutrient content of waste in primary anaerobic dairy lagoons. This was accomplished through a monitoring study of twelve dairy operations that investigated eight management variables and their influence on anaerobic lagoon effluent quality. These variables include removal of lagoon solids, flush water type, solid separation, manure sources, bedding type, number of cells, lagoon age, and herd size. The impact of dairy waste management practices was then examined to ascertain the impact on land area requirements for land disposal of lagoon waste, in relation to more rigorous P-based regulations.

Materials and Methods

Statistical analyses for a study of this nature are unreliable due to the large number of unknown and conflicting variables. Two seemingly similar lagoons may deviate in performance efficiency based on an incalculable number of factors (e.g., variations in feed type, differences in bedding quality and quantity). Due to the uncontrolled character of this study, mean and standard deviation data are provided; however, this is intended to ascertain trends in lagoon function and not designed to generate definitive cause and effect relationships.

The sludge accumulation in twelve primary cells of anaerobic dairy lagoons in Erath (7 lagoons, 8 to 11 years old), Comanche (3 lagoons, 10 to 14 years old), and Hamilton (2 lagoons, 6 to 8 years old) counties in central Texas was evaluated. In addition, physicochemical characteristics of the lagoon slurry (the readily pumpable material henceforth referred to as slurry mix) were determined. The herd size per operation ranged from 200 to 2,500 cows. Sand, composted manure, or cotton gin refuse was used as bedding material in the free-stall barns. The primary cell received waste from a variety of sources including feed alleys, milking parlors, holding pens, and open lots.

A flat-bottom boat was used to navigate each lagoon for depth and slurry mix sampling at various locations. To assess the extent of sludge accumulation, total depth (from top of the liquid level to lagoon bottom), slurry mix depth (from top of the liquid level to top of dense sludge level), and dense sludge depth (the difference between total depth and slurry mix depth) were measured using two 2.4 m sections of a 2.54 cm diameter graduated (markings 5 cm apart) metal conduit with an end cap (fig. 1). At the midline of each lagoon, starting approximately 6 m downstream of the inlet, the conduit was lowered vertically into the lagoon until it rested on top of the dense sludge. This depth was noted and recorded as the slurry mix depth. Then the conduit was pushed into the dense sludge until it rested at the bottom of the lagoon and could no longer be pushed through the dense sludge. This depth was noted and recorded as the total depth of the lagoon. This procedure was repeated two to three times within a 2 m^2 area of each location to verify these depths. Then the entire procedure of depth measurements was repeated at four more locations at regular intervals to the lagoon center (fig. 2).

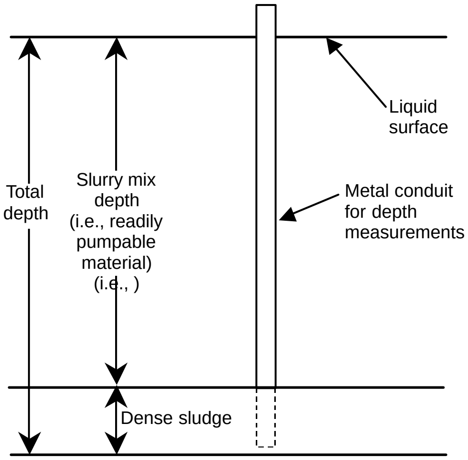

Figure 1. Lagoon sludge measurement scheme.

A representative slurry sample was collected in conjunction with each of the depth readings at the five sampling locations in each lagoon for analysis of the following parameters: pH, total solids (TS), volatile solids (VS), total Kjeldahl nitrogen (TKN), total ammonium-nitrogen (NH_4-N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), zinc (Zn), copper (Cu), manganese (Mn), and electrical conductivity (EC). Samples were collected with the Sludge Judge (Nasco, Fort Atkinson, Wisc.), a sampling device consisting of three 1.5 m sections of 3.18 cm diameter acrylic pipe and a ball check valve at the bottom end. The sampler was lowered slowly until it rested on top of the dense sludge, filling the pipe and providing a composite of the entire lagoon depth profile; the check valve trapped the slurry mix as the device was raised. The sample was subsequently emptied into a plastic bucket, mixed thoroughly to simulate an agitated mixture of supernatant and sludge, and stored in a 1 L plastic bottle. The samples remained in an ice-filled cooler during transport and were kept at 4°C until chemical analysis occurred within 48 h. All chemical and solids analyses were performed according to the methods listed in table 1 at the Soil, Water, and Forage Testing and Water Quality Testing laboratories of Texas A&M University.

Results and Discussion

Composition of Anaerobic Lagoon Slurries

Table 2 presents mean values and standard deviations of slurry mix analyzed from samples of the twelve lagoons. For comparison, previously reported dairy lagoon slurry (Barker et al., 2001) and anaerobic dairy lagoon (MWPS, 2001) characteristics are included. Total lagoon depth and slurry mix depth varied somewhat for all lagoons, but averages of 3.32 m and 2.65 m were measured for total and slurry mix

Figure 2. Sampling scheme of a representative lagoon with sludge depths and chemical analysis performed at each location indicated (fifth sampling location not shown).

Table 1. Analytical methods used to analyze lagoon slurry samples.

Variables	Sample Preparation	Analytical Method
Total solids	Drying at 105°C	Standard Method 2540 B (APHA, 1995)
Volatile solids	Combustion at 550°C	Standard Method 2540 E (APHA, 1995)
pH and electrical conductivity	Probe	Omega PHH-500 Series water analyzer
TKN	Digest in sulfuric acid-hydrogen peroxide, analysis by ICP	Digester, Nelson and Sommers (1973)
P, K, Ca, Mg, Na, Zn, Fe, Cu, Mn	Elemental analysis by ICP	Angel and Feagley (1987)

Table 2. Summary statistics of all dairy lagoon parameters.[a]

	Central Texas Dairy Lagoon Slurry (*n* = 12)		North Carolina Dairy Lagoon Slurry (*n* = 15)[b]		Anaerobic Dairy Lagoon[c]
Parameter	Mean	SD	Mean	SD	
Total depth (m)	3.32	0.76	--	--	--
Slurry mix (m)	2.65	1.07	--	--	--
Dense sludge (m)	0.46	0.70	--	--	--
Sludge depth (%)[d]	16.5	3.4	--	--	--
TS (%)	4.32	2.63	7.0	2.9	--
VS (%)	2.43	0.58	--	--	--
pH	7.48	0.28	7.1	0.46	--
TKN (mg/L)	1892	828	17,591	374	347 - 659
NH_4-N (mg/L)	303	140	--	--	204 - 348
P (mg/L)	470	238	733	345	94 - 194
K (mg/L)	1379	499	2000	870	370 - 739
Ca (mg/L)	1800	1600	1200	708	--
Mg (mg/L)	400	100	600	336	--
Na (mg/L)	357	123	372	204	--
Zn (mg/L)	19.0	10.5	22.8	14.4	--
Fe (mg/L)	17.8	16.3	228	192	--
Cu (mg/L)	12.3	14.4	5.52	4.1	--
Mn (mg/L)	17.0	10.1	21.6	9.6	--
EC (µS/cm)	7324	2913	7191	2520	--

[a] All concentrations on as-is or wet basis; SD = standard deviation.
[b] Barker et al. (2001).
[c] MWPS (2001).
[d] Percent dense sludge depth compared to total depth.

depths, respectively. As indicated by the large standard deviation (0.7 m), mean dense sludge depth (0.46 m) varied highly for all lagoons. In fact, dense sludge depths varied from nearly zero to almost 1.7 m. Comparing the dense sludge depth to the total depth (an indicator of encroachment of sludge on the treatment volume) shows an average of 16.5% of the total depth was occupied by dense sludge.

Mean TS for all lagoons was 4.32%, and the mean VS value (2.43%) was nearly half of the mean TS. In addition, mean TS for the slurry mix was less than the TS reported by Barker et al. (2001) but much higher than about 1% TS generally found in the top 0.5 to 1 m of the supernatant in an anaerobic dairy lagoon.

Mean pH of the slurry mix (7.48) varied little for all lagoons and was well above pH 6.5, where acidic conditions may generate excessive odors in anaerobic lagoons. Table 2 also shows high variability in TKN, NH_4-N, P, K, and measured salts and metals within the dairy lagoons. This finding corresponds to the high variability displayed by the data reported by Barker et al. (2001). Generally, similar values were observed for the slurry mix and the Barker data. One notable exception to this trend involved Fe, with concentrations averaging 10 times lower than the values reported by Barker et al. (2001). Although no definitive explanation was explored, variations in feed composition may account for this discrepancy. As compared to the effluent values (MWPS, 2001) of TKN, P, and K, both the slurry mix and Barker et al. (2001) had much higher concentrations for these parameters.

EFFECT OF MANAGEMENT PRACTICES ON SLURRY MIX AND SLUDGE ACCUMULATION

The nature of this study prevents rigorous statistical analysis of management practice impact on physicochemical parameters due to the impossibility of achieving precise replication for lagoon operations. However, a number of trends can be identified for further investigation to determine

Table 3. Management practice effects on physicochemical properties of slurry mix.

Management Practice	No. of Lagoons	TS (%)		VS (%)		pH		EC (ds/m)		TKN (mg/L)		P (mg/L)		K (mg/L)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Removal of solids															
Not since built	5	4.9	3.4	2.6	0.3	7.5	0.2	6745	3245	1919	1070	463	268	1452	535
Since built	7	3.9	1.9	2.3	0.3	7.5	0.2	7754	2612	1872	608	475	219	1323	472
Flush water															
Fresh	4	4.1	2.9	2.2	0.3	7.3	0.2	4538	1078	1908	985	442	222	1033	391
Recycled	5	5.3	2.5	3.1	0.3	7.5	0.2	9522	2814	2210	719	588	226	1824	274
Combination (fresh/recycled)	3	2.9	2.0	1.6	0.3	7.5	0.2	6742	634	1330	480	288	145	1010	216
Solid separation															
Settling basin	7	3.7	2.5	2.1	0.2	7.5	0.2	6573	2531	1761	786	438	229	1275	477
Mechanical	3	4.7	1.6	2.6	0.3	7.4	0.1	9879	2660	1907	672	498	263	1582	557
Both	1	8.0	3.1	4.4	0.3	7.4	0.2	6092	2635	2799	1060	626	207	1594	296
Open lot runoff															
Not included	2	2.3	1.5	1.4	0.1	7.6	0.2	6878	599	1382	512	289	139	1097	182
Included	10	4.8	2.6	2.7	0.4	7.4	0.2	7426	3213	2008	846	507	238	1443	527
Bedding type															
None	4	3.2	2.0	1.8	0.3	7.4	0.1	5528	1170	1553	630	357	200	841	127
Sand	4	3.5	2.0	2.0	0.3	7.6	0.2	9556	2537	1756	591	469	228	1725	376
Gin trash	2	5.6	3.0	2.8	0.2	7.3	0.1	4630	1460	2045	1212	442	226	1259	434
Composted manure	1	5.7	0.4	3.4	0.0	7.4	0.1	10496	974	2412	478	750	200	1865	35
No. of cells															
1	1	5.7	0.4	3.4	0.0	7.4	0.1	10496	974	2412	478	750	200	1865	35
2	8	4.3	2.6	2.5	0.4	7.5	0.2	8015	2632	1828	781	445	222	1449	473
3	2	2.6	1.7	1.5	0.1	7.4	0.2	4445	579	1770	753	441	234	807	148
4	1	5.8	3.9	2.5	0.1	7.3	0.2	3786	1089	2030	1444	417	272	1296	545
Lagoon age															
10 years or less	7	4.7	3.0	2.5	0.3	7.5	0.2	7408	3030	1950	940	511	266	1528	469
11 years or more	5	3.7	1.9	2.2	0.3	7.4	0.1	7193	2786	1802	623	408	177	1144	462
Herd size															
Less than 1000	4	4.4	2.0	2.6	0.2	7.6	0.2	8597	2813	2128	507	620	210	1611	478
1000 to 1499	6	3.7	2.6	1.9	0.4	7.4	0.2	5711	1523	1507	849	325	188	1047	341
More than 2000	2	6.0	3.3	3.6	0.5	7.4	0.1	8977	3900	2437	910	524	201	1784	308

the most influential management practices to improve treatment effectiveness (table 3). Analysis of variance (at a 95% confidence level) was performed on those practices that appeared to exhibit divergent values; however, it should be noted that the rudimentary analysis should be taken with a degree of uncertainty due to low sample numbers and a myriad of conflicting variables that cannot be isolated due to the research design. Therefore, in some instances, discussion on management practices will involve cases that show a trend but do not display a statistical difference in this study.

Initial values obtained for fresh and recycled flush water indicate that fresh flush water reduces values for all parameters, with a significant decrease in conductivity. Statistical analysis showed that there was no explicit difference for sludge accumulation, total solids, TKN, P, or K, whereas NH_4 and EC did show a statistical difference. It is hypothesized that the use of fresh water likely asserts a dilution effect that improves lagoon effluent quality. This is not surprising, as flush systems use large quantities of water, on the order of 345 L per cow per day (Ritchie, 1977; Van Horn et al., 1993). No explanation was developed to explain why a combination of fresh and recycled flush water further reduced total and volatile solids and TKN, P, and K (statistical differences were only found for sludge accumulation, NH_4, and conductivity) as the relative proportions for each operation were unknown; however, this may provide an effective compromise between fresh versus recycled systems. It should be noted that solids may accumulate within the system when recycled lagoon water is used for flushing.

Sludge accumulation and total solids and nutrient value reductions were observed with increasing treatment cell number. Statistical analyses found no clear difference between physicochemical values between operations with single-cell versus dual-cell systems, but disparities arose when each of these system types was compared to a three-cell array. A three-cell system showed significant differences over a single-cell design in TS and TKN and similarly showed enhanced performance over a dual-cell system for TKN and P (likewise for TS at a 90% confidence level). The single four-cell system examined showed reduced performance characteristics, which can be postulated as an anomaly due to other management factors employed at this locale. These findings likely can be attributed to increased settling time for solids and associated nutrients in conjunction with a longer period over which biological activity can progress. Increasing the number of treatment cells appears to have a beneficial impact on lagoon water quality.

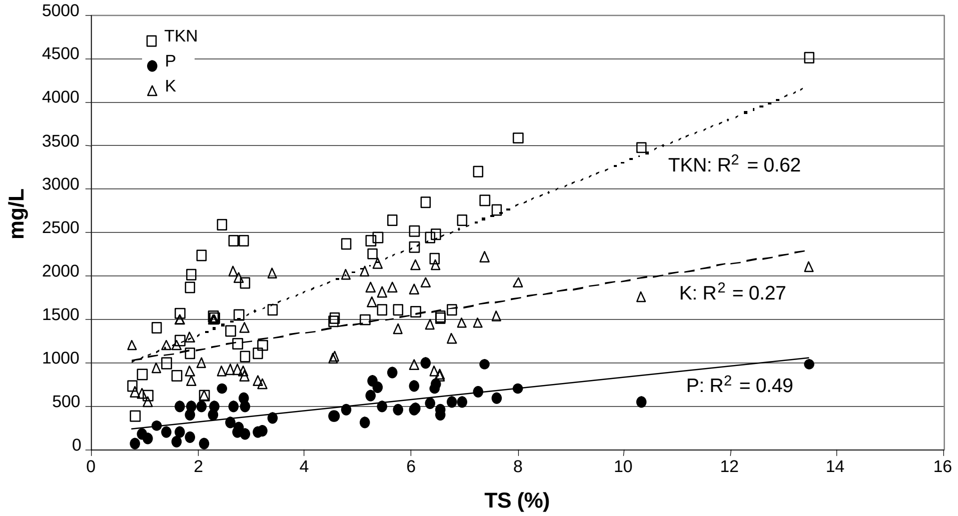

Figure 3. Correlation of total solids with TKN, P, and K from slurry mix samples of all lagoons.

The inclusion of dry lot runoff into the lagoon system appears to increase total and volatile solids, conductivity, and nutrient values with statistically different findings determined for sludge accumulation at a 90% confidence level, TS, TKN, and K. This is not unexpected, as the bare soil media and amassed manure residue comprising the dry lots likely increases sediment transport to the lagoon system. Therefore, it appears that separation of dry lot runoff from waste originating from feeding alleys, milking parlors, and holding pens may reduce sludge accumulation and nutrient content. However, a dairy operation needs to evaluate the costs associated with installation and management of a separate lagoon system for dry lot runoff compared to the apparent benefits. Furthermore, the same waste volume will be produced regardless, and thus the disparate potency of the waste streams and the intermittent nature of the dry lot runoff may be considered in developing alternative treatment strategies.

Both the number of treatment cells and inclusion of dry lot runoff variables seem intrinsically linked to solid removal from the waste stream. Correspondingly, nutrient values decreased with diminishing solids content. Figure 3 illustrates correlation of TS with TKN, P, and K concentrations of all slurry mix samples. Best fit, linear trend lines are shown. Generally, concentrations of all nutrients increased linearly with an increase in TS, but TKN had the highest correlation ($R^2 = 0.62$) followed by P ($R^2 = 0.49$) and K ($R^2 = 0.27$). In light of these positive relationships, the idea for the need of solid separation becomes more evident to improve lagoon effluent quality. The relatively weak correlation between TS and P was surprising, as P typically shows strong association with solids through either adsorption or precipitation mechanisms (Rhue and Harris, 1999). Reasons for this finding are speculative and require further investigation, but one possibility includes an intrinsically lower number of binding sites associated with the solids in these waste streams (e.g., high silicate content of effluent originating from operations using sand bedding will resist P binding).

Liquid-solid separation presents a common method to reduce sludge accumulation in anaerobic lagoons and to improve pumping and irrigation characteristics of lagoon effluent. Although all dairy operations sampled in this study used some form of solid separation prior to discharge of waste to the anaerobic lagoons for comparison, the use of gravity separation (i.e., settling basins) or mechanical separation has been shown to greatly reduce sludge accumulation (Zhang and Westerman, 1997). Furthermore, liquid-solid separation generates solids for composting that can be used for bedding or sold as a plant media to local distributors. Recent research has shown that solid separation can be further enhanced using flocculants (Karthikeyan et al., 2002; Sherman et al., 2000; Barrow et al., 1997). Moore (1989) presents a review of the advantages of different techniques for dairy manure solid separation.

Bedding type may also influence the parameter values measured in this study. Where no bedding is used (i.e., dry lot dairy operations with no additional material used), TS, VS, TKN, P, and K values are consistently lower than for operations using some form of bedding media (i.e., sand, gin trash, composted manure). Furthermore, composted manure used as bedding resulted in elevated concentrations, as much as two-fold higher TS values compared to no bedding samples; gin trash similarly raised TS and TKN concentrations. Herd size may similarly impact these same parameters. When herd size ranged from 1000 to 1499 dairy cows, values were lower than when herds were less than 1000 or greater than 2000 animals (analysis of variance showed statistically significant differences in P and conductivity). This finding may suggest an economic optimization that would require further study. However, inferring definitive cause and effect relationships between bedding type and herd size would be erroneous at this time considering the study limitations.

IMPLICATIONS ON LAND AREA REQUIRED FOR ON-SITE EFFLUENT APPLICATION

Large dairy operations are subject to compliance with concentrated animal feeding operation (CAFO) regulations that govern manure land application. Although some dairy operations may have sufficient acreage to dispose of lagoon effluent according to agronomic N needs, a shift towards P-based nutrient management could result in land limitations. An analysis of land requirements for application based on the lagoon slurry mix characteristics to meet P regulations was performed. Table 4 lists the criteria used to determine the number of hectares needed. Crop nutrient requirements were

Table 4. Parameters used in calculating land area needed for lagoon slurry disposal.

Crop	Hybrid Bermuda with one hay cutting and two grazings.
Application	One application with none applied following graze down.
Crop nutrient requirements	246, 112, and 336 kg/ha for N, P_2O_5, and K_2O, respectively.
N behavior	50% of organic form available for plant use; 25% of total N lost due to volatilization during surface application; no credit of N carryover from previous effluent applications.
N applied	437.0 kg/ha (recommended application rate to accommodate for availability and losses).

based on Texas Cooperative Extension recommendations, and all P_2O_5 and K_2O are considered available for plant use.

Figure 4 illustrates the number of hectares hypothetically required if 378 m^3 (100,000 gallons; used as a representative pump-out event) of slurry mix from the sampled dairy lagoons were to be land applied based on the N and P needs of the hay/grazing crop. As a comparison, land area requirements for application of the same volume of lagoon effluent based upon published average values (MWPS, 2001) of 0.50 and 0.33 kg/m^3 of TKN and P_2O_5, respectively, are included.

Based on these criteria, it can be seen that the P-based land area required would be as high as two and a half times the area needed for an equal volume of effluent applied at N-based rates, considering published effluent values, and over two times that required when considering a slurry mixture. Furthermore, over a three-fold increase in land area would be required when using values of the simulated agitated lagoon material compared to published effluent values. Dairy operations therefore need to carefully sample lagoons to determine the actual nutrient content of the land-applied material, rather than depending on a supernatant sample or published values to provide realistic estimates of the nutrient contents of a specific lagoon.

Removal and utilization of this high moisture (90% to 95% water) slurry mix presents a nutrient and waste management challenge for producers. To avoid soil and water pollution from excess N and P, additional land is required to apply manure, and in most instances, it has to be transported to distant fields with low levels of soil P. Daugherty et al. (2001) performed a cost comparison for transport and application of dairy waste slurries considering herd size, transport distance, and nutrient application rates. Analysis showed shifts toward P-based management systems increased costs from 5% to 60% depending on dairy operation specifics. Therefore, dairy waste management decisions have significant implications on economic viability. A slurry removal and management method that will significantly reduce volume by decreasing the moisture content of sludge would reduce the cost of transportation, lagoon renovation, and maintenance.

In addition, strategies to reduce P in lagoon effluent must be addressed by many dairy operations to allow for continued on-site land disposal. Reducing the P import to dairy facilities can further aid producers in meeting P-based regulations while concurrently reducing costs to dairy operations. In addition to using lagoon effluent as a substitute for commercial fertilizers, changes in cropping practices may further improve the off-site transport of P (Rotz et al., 2001). Recently released findings by NRC (2001) show dietary P requirements for dairy cattle are lower than previously reported. Therefore, reducing mineral P dietary supplements will diminish excess excreted P while improving farm profitability by more than $20 per cow (Rotz et al., 2001).

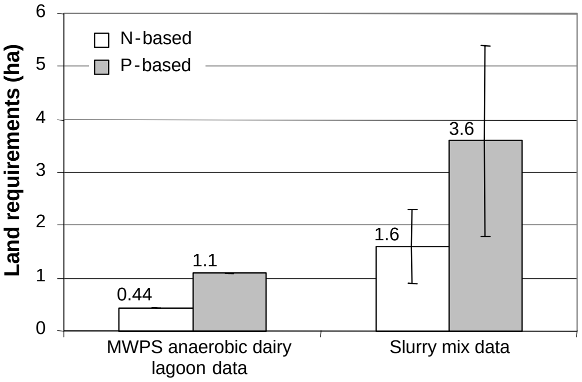

Figure 4. N-based and P-based land needed to apply 378 m^3 (100,000 gallons) of dairy lagoon effluent based on MWPS values and slurry mix findings.

Other innovative strategies may assist dairy facilities in moderating P problems. Recent research has shown that duckweed introduced to swine lagoon liquid significantly reduced nitrogen and phosphorus concentrations (Cheng et al., 2002). Constructed wetlands have shown promise in improving effluent quality from livestock operations. Hunt et al. (2002) found vegetated wetlands effectively reduced nitrogen from anaerobic lagoons treating swine wastewater, but further augmentation might be required for phosphorus removal. Artificial wetlands receiving dairy wastewater from an aerobic holding pond improved solids, BOD, and nutrient concentrations (Tanner et al., 1995a, 1995b). Although these emerging technologies may prove suitable for some operations, their overall economic viability remains unclear.

CONCLUSION

This on-site dairy facility study illustrates the high degree of variability of lagoon physicochemical characteristics. From this rudimentary analysis, three main operation and maintenance factors were ascertained. First, the use of fresh water likely asserts a dilution effect that improves lagoon waste quality. Second, increasing the number of treatment cells appears to have a beneficial impact on lagoon water quality. Finally, separation of dry lot runoff from waste originating from feeding alleys, milking parlors, and holding pens may reduce lagoon sludge accumulation and nutrient content. Each of these management types resulted in diminished sludge accumulation, with statistically significant differences for operations that included separated dry lot runoff. Furthermore, preliminary indications suggest that bedding type and herd size may also influence parameter values. It is important to note that unidentified factors and confounding variables may obscure the impact of different management practices. However, proper lagoon management will extend lagoon longevity by reducing sludge accumulation and help defer closure or renovation costs.

The impact of management on lagoon effluent quality also has implications on the ability of dairies to meet more rigorous P-based land application regulations. Positive correlations between TS and TKN, P, and K suggest that reducing the solid load to lagoons will help decrease the required land area to achieve nutrient management goals.

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REFERENCES

Angel, C. E., and S. E. Feagley. 1987. The effect of lime and fertilizer on four lignite overburdens under non-drained conditions: 1. Yield and nutrient concentration of common Bermudagrass. *Comm. Soil Science and Plant Analysis* 18(9): 963-980.

APHA. 1995. *Standard Methods for Examination of Water and Wastewater.* 19th ed. Washington, D.C.: American Public Health Association.

ASAE Standards, 49th ed. 2002. EP403.2: Design of anaerobic lagoons for animal waste management. St. Joseph, Mich.: ASAE.

Barker, J. C., J. P. Zublena, and F. R. Walls. 2001. Animal and poultry manure production and characterization. North Carolina Cooperative Extension Service. Available at: www.bae.ncsu.edu/people/faculty/barker/a&pmp&c/. Accessed on 21 Jan. 2003.

Barrow, J. T., H. H. Van Horn, D. L. Anderson, and R. A. Nordstedt. 1997. Effects of Fe and Ca additions to dairy wastewaters on solids and nutrient removal by sedimentation. *Applied Eng. in Agric*. 13(2): 259-267.

Bicudo, J. R., L. M. Safley, and P. W. Westerman. 1999. Nutrient content and sludge volumes in single-cell recycle anaerobic swine lagoons in North Carolina. *Trans. ASAE* 42(4): 1087-1093.

Cheng, J., L. Landesman, B. A. Bergmann, J. J. Classen, J. W. Howard, and Y. T. Yamamoto. 2002. Nutrient removal from swine lagoon liquid by *Lemna minor* 8627. *Trans. ASAE* 45(4): 1003-1010.

Daugherty, A. S., R. T. Burns, T. L. Cross, D. R. Raman, and G. F. Grandle. 2001. Liquid dairy waste transport and land application cost comparisons considering herd size, transport distance, and nitrogen versus phosphorus application rates. ASAE Paper No. 012263. St. Joseph, Mich.: ASAE.

Hunt, P. G., A. A. Szögi, F. J. Humenik, J. M. Rice, T. A. Matheny, and K. C. Stone. 2002. Constructed wetlands for treatment of swine wastewater from an anaerobic lagoon. *Trans. ASAE* 45(3): 639-647.

Karthikeyan, K. G., M. Z. Tekeste, M. Kalbasi, and K. Gungor. 2002. Chemical treatment of dairy manure using alum, ferric chloride, and lime. ASAE Paper No. 024093. St. Joseph, Mich.: ASAE.

Miner, J. R., F. J. Humenik, and M. R. Overcash. 2000. *Managing Livestock Waste to Preserve Environmental Quality.* Ames, Iowa: Iowa State University Press.

Moore, J. 1989. Dairy manure solid separation. In *Proc. Dairy Manure Management Symposium (NRAES-31)*, 178-194. Ithaca, N.Y.: Natural Resource, Agriculture, and Engineering Service (NRAES).

MWPS. 2001. Manure storages. Manure Systems Series. Publ. No. MWPS-18 Section 2. Ames, Iowa: Midwest Plan Service.

Nelson, D. W., and L. E. Sommers. 1973. Determination of total nitrogen in plant material. *Agronomy J*. 65(1): 109-112.

NRC. 2001. *Nutrient Requirements of Dairy Cattle*. 7th rev. ed. Washington, D.C.: National Resource Council, National Academy Press.

Rhue, R. D., and W. G. Harris. 1999. Phosphorus sorption/desorption reactions in soils and sediments. In *Phosphorus Biogeochemistry in Subtropical Ecosystems*, 187-206. K. R. Reddy, G. A. O'Connor, and C. L. Schelske, eds. Boca Raton, Fla.: Lewis Publishers.

Ritchie, R. M., Jr. 1977. Long alley flushing of dairy cattle facilities in warmer climates. ASAE Paper No. 774563. St. Joseph, Mich.: ASAE.

Rotz, C. A., A. N. Sharpley, W. J. Gburek, M. A. Sanderson, and L. D. Satter. 2001. Production and feeding strategies for phosphorus management on dairy farms in New York. ASAE Paper No. 012013. St. Joseph, Mich.: ASAE.

Safley, L. M., Jr., and P. W. Westerman. 1992. Performance of a dairy manure anaerobic lagoon. *Bioresource Tech.* 42(1): 43-52.

Sherman, J .J., H. H. Van Horn, and R. A. Nordstedt. 2000. Use of flocculants in dairy wastewaters to remove phosphorus. *Applied Eng. in Agric*. 16(4): 445-452.

Tanner, C. C., J. S. Clayton, and M. P. Upsdell. 1995a. Effect of loading rate and planting on treatment of dairy farm wastewaters in constructed wetlands - I. Removal of oxygen demand, suspended solids, and faecal coliforms. *Water Resources* 29(1): 17-26.

Tanner, C. C., J. S. Clayton, and M. P. Upsdell. 1995b. Effect of loading rate and planting on treatment of dairy farm wastewaters in constructed wetlands - II. Removal of nitrogen and phosphorus. *Water Resources* 29(1): 27-34.

Van Horn, H. H., D. R. Bray, R. A. Nordstedt, R. A. Bucklin, A. B. Bottcher, R. N. Gallaher, C. G. Chambliss, and G. Kidder. 1993. Water budgets for Florida dairy farmers. Circular No. 1091. Gainesville, Fla.: University of Florida, Institute of Food and Agricultural Sciences, Florida Cooperative Extension Service, Department of Dairy Science.

Zhang, R. H., and P. W. Westerman. 1997. Solid-liquid separation of animal manure for odor control and nutrient management. *Applied Eng. in Agric*. 13(5): 657-664.