Nitrogen Dynamics in Covered Swine Lagoons

Final Report

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Introduction

Impermeable covers have been tested on existing swine lagoons in North Carolina as an incremental process for addressing environmental standards for swine farms. Potential benefits of lagoon covers include reduction in emissions of odor, ammonia, fine particulate matter precursors, and greenhouse gases. At the same time, revenue could be generated by selling carbon credits resulting from reduction in methane emissions, and/or by generating electricity from the methane collected. However, there could also be unintended effects from a cover on an existing lagoon. Such covers present a barrier to volatilization and to wind mixing that are typical of traditional open lagoons. Possible effects include increased nitrogen concentrations in the lagoon liquid and altered build-up rate or distribution of sludge solids in the lagoon. Demonstration projects on four swine lagoons in North Carolina present an opportunity to learn what effects lagoon covers will have on lagoon characteristics and to explore nitrogen management strategies. The goal of this research was to evaluate the changes in lagoon dynamics that occurrred as a result of covering a swine lagoon with a non-permeable cover.

Nitrogen concentrations have increased substantially since the beginning of this study. We know that additional nitrogen management will be required with these covers. With the higher concentration of nitrogen in the lagoon liquid, recovery of reactive nitrogen (rather than destruction or dispersion) may become energetically and economically favorable. Thus, we also evaluated possible options for nitrogen recovery from covered lagoon liquid; including ammonia stripping, algal growth for biodiesel production, and membrane separation technology; and analyzed the effect of nitrogen recovery associated with lagoon covers on the carbon footprint of swine production in North Carolina.

Changes in Nitrogen Concentrations in Covered Lagoons

Environmental Credit Corp. (ECC) received funding from the USDA NRCS Conservation Innovation Grant (CIG) program for the purpose of demonstrating covered lagoons in an innovative carbon credit incentive program. Four swine lagoons on two separate farms in North Carolina were covered as part of this program. Covers were installed on all four lagoons in April, 2008, and monitoring was initiated in May, 2008.

Methods

The evaluation plan for this project included monitoring nitrogen concentrations in the lagoons prior to cover installation for comparison. However, cover installation was already in progress when this study began, and thus we did not have an opportunity to monitor nitrogen levels before the covers were put in place. We do have previous data from the NC Department of Agriculture (NCDA) laboratory, which was analyzed as part of the farmers' monitoring programs under normal operating conditions. These data were compared to post-cover levels at both farms. During this study, samples were collected from May, 2008, through August, 2010. The lagoon covers are completely sealed around the lagoon edges. Liquid samples were collected through the 0.6 m (24 inch) diameter ports in the cover that were installed to allow irrigation lines to be placed in the lagoon. A closed sampler was lowered into the lagoon to a depth of 45 cm (18 inches). The sampler was opened and filled at that depth and then closed before being brought to the surface. This depth was chosen to avoid contamination with sludge that would result from disturbing the sludge layer, and to avoid floating matter on the surface of the liquid. Samples were collected one or two times per month. Samples were analyzed at the Environmental Analysis Laboratory at NC State University (NCSU) for nitrogen compounds, phosphorus, solids, and alkalinity.

Results

Nitrogen species analyzed at NCSU included total Kjeldahl nitrogen (TKN), total ammoniacal nitrogen (TAN), and nitrate plus nitrite. TKN includes all reduced forms of nitrogen (suspended organic, dissolved organic, and ammoniacal nitrogen). Nitrate plus nitrite concentrations were always negligible, so TKN measurements represent total nitrogen (TN).

Total nitrogen concentrations in the two lagoons at each farm before (NCDA data) and after (NCSU data) covers were installed are shown in Figures 1 and 2, along with average monthly air temperatures. Concentrations became much higher in the covered lagoon than the average concentrations measured by NCDA before cover installation. However, we have observed inconsistencies between data provided by the NCDA analysis and the sample analysis conducted at NCSU, and therefore will not emphasize the comparison before and after the cover installation. The data before the cover installation is interesting, however, in showing a seasonal cyclical pattern of nitrogen concentrations in the uncovered lagoons. Concentrations tend to increase during the cool parts of the year and decrease during the warmer seasons. Mechanisms for this decrease are volatilization of ammonia and microbial oxidation of ammonium to nitrate, followed by microbial denitrification to N_2. Both of these processes are enhanced at higher temperatures. Covers were installed in the month of April, which is typically a relatively high point in the nitrogen concentration cycle of uncovered lagoons. Therefore, the starting point of these covered lagoons was probably near the highest concentration of their natural cycle. The covered lagoons do not have such a cycle because the cover prevents both volatilization and presence of oxygen, which is required for the oxidation of ammonium.

A more reliable method of determining the amount of nitrogen increase in the covered lagoons is to compare concentrations throughout the study, using data that were analyzed at the same laboratory. Nitrogen concentrations increased substantially in all four lagoons after cover installation, although the actual rate of change was not constant (Figures 3 and 4). The amount of increase was determined using the difference in estimated concentrations at the beginning and the end of the study. Initial concentrations were estimated using a best-fit linear trendline through the first six months of data points. The final concentrations were estimated as the average over the last four months, when concentrations appeared to be fairly steady. By this method, the total nitrogen concentrations at Farm 1 increased by 72% and 115% in Lagoons 1 and 2, respectively. At Farm 2, nitrogen concentrations increased by 107% and 102% in Lagoons 3 and 4, respectively (Table 1).

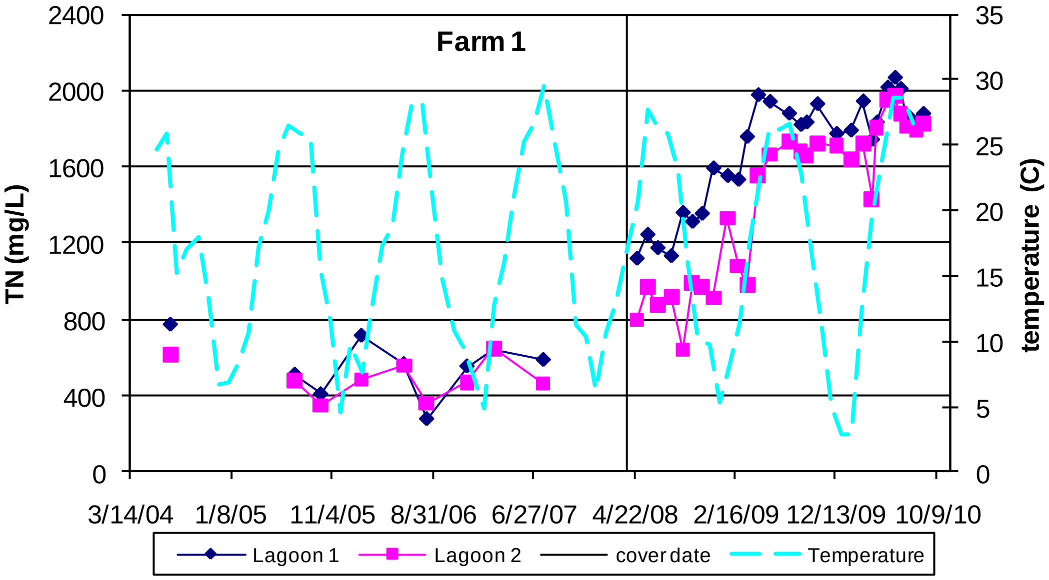

Figure 1. Total nitrogen (TN) concentrations from Farm 1 (Lagoons 1 and 2).

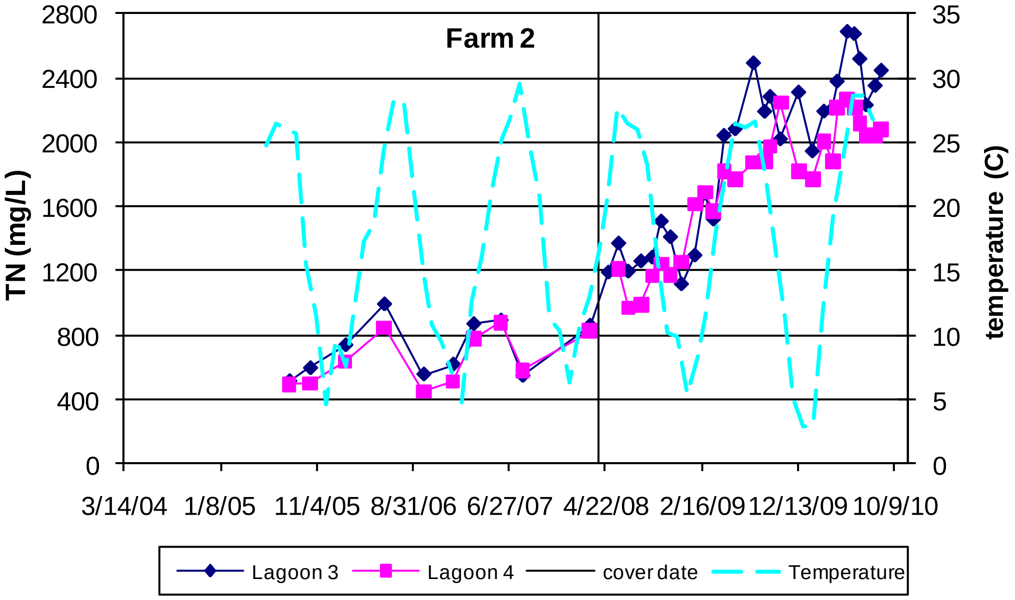

Figure 2. Total nitrogen (TN) concentrations from Farm 2 (Lagoons 3 and 4).

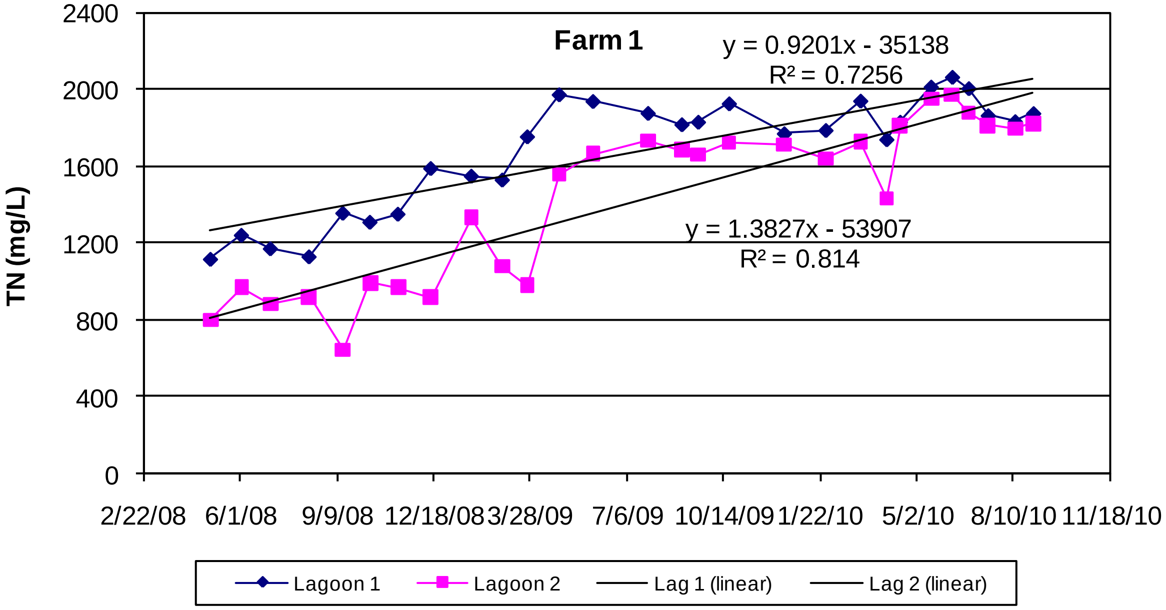

Figure 3. Total nitrogen concentrations at Farm 1 (Lagoons 1 and 2) after cover installation.

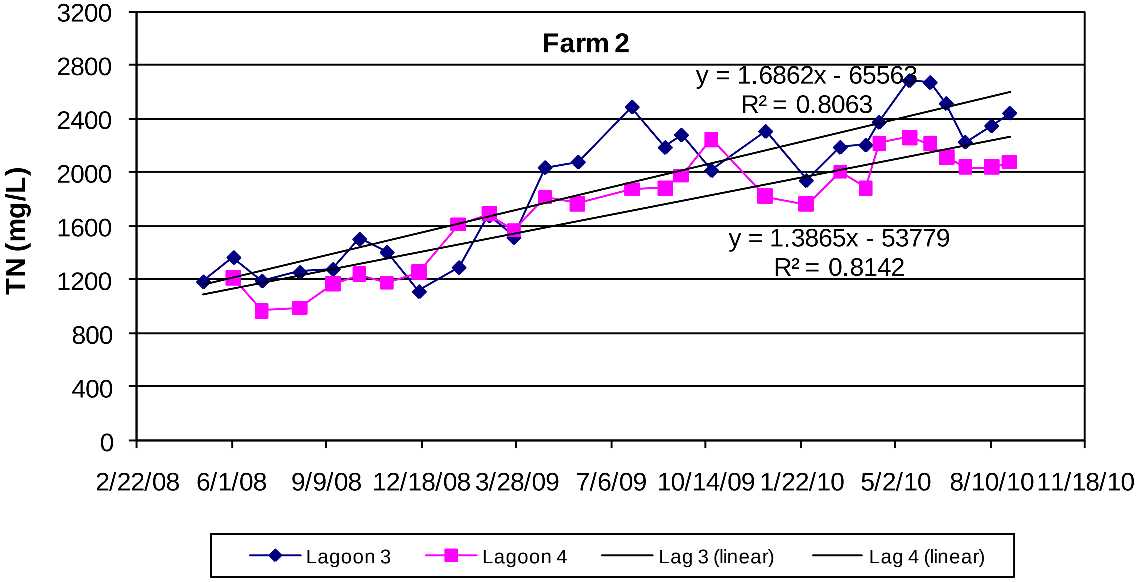

Figure 4. Total nitrogen concentrations at Farm 2 (Lagoons 3 and 4) after cover installation.

Table 1. Estimated Total Nitrogen (TN) and Total Ammoniacal Nitrogen (TAN) Concentration Increases During the Evaluation Period.

	Total Nitrogen (TN)			Total Ammoniacal Nitrogen (TAN)		
	Initial mg/L	Final mg/L	% Increase	Initial mg/L	Final mg/L	% Increase
Lagoon 1	1130	1940	72%	963	1770	84%
Lagoon 2	869	1870	115%	720	1730	140%
Lagoon 3	1200	2480	107%	1020	2270	122%
Lagoon 4	1050	2120	102%	860	1970	129%

Total nitrogen concentrations appeared to stabilize over the last six months of the study, indicating that maximum levels may have been reached. However, TAN concentrations appeared to still be increasing, although not at as great a rate as previously (Figures 5 and 6). Total nitrogen includes particulate organic nitrogen, and therefore has a component that is correlated with suspended solids. Suspended solids concentration in the lagoons was highly variable, and it is impossible to determine the effect they might have had on total nitrogen. The TAN concentrations, however, indicate that nitrogen might have still be increasing at the end of the evaluation, although slowly.

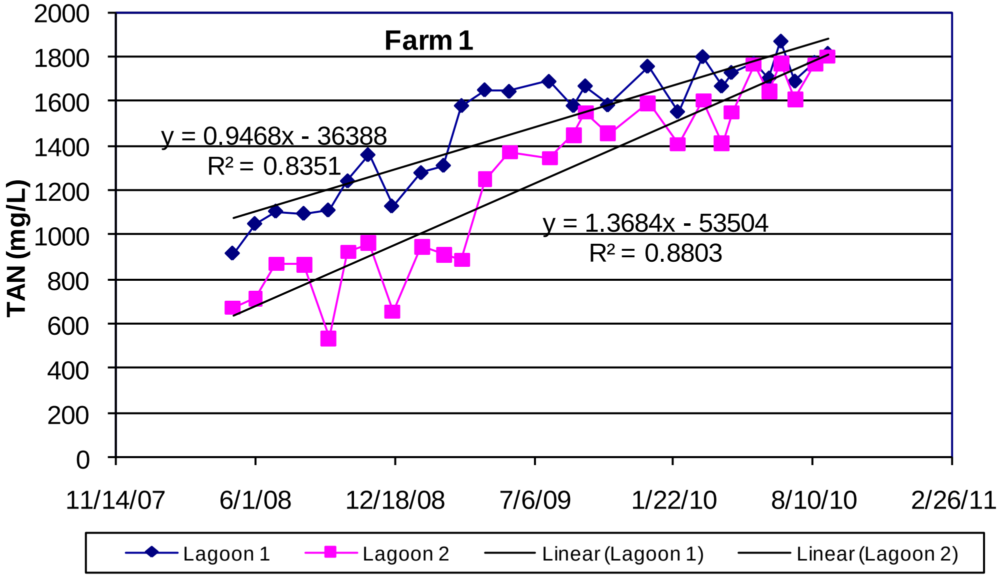

Figure 5. Total ammoniacal nitrogen (TAN) concentrations at Farm 1 (Lagoons 1 and 2) after cover installation.

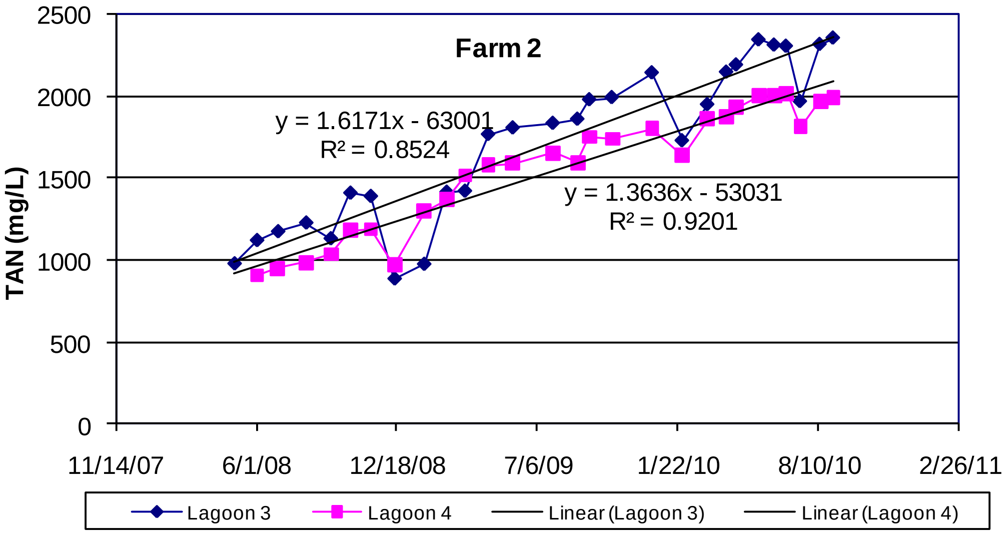

Figure 6. Total ammoniacal nitrogen (TAN) concentrations at Farm 2 (Lagoons 3 and 4) after cover installation.

Another beneficial effect of impermeable covers is that they exclude rainwater. Although nitrogen levels have clearly increased during this evaluation period, part of the increased concentration may be due to the lack of dilution by rainwater. We were not able to collect data to calculate a complete water balance for the system, so we do not know how much of the nitrogen concentration increase was due to exclusion of rainwater from the lagoons and how much was due to prevention of volatilization of ammonia gas. An approach to determine dilution effect is to compare concentrations of non-reactive compounds or salts, frequently referred to as tracers. Chloride is a very good tracer substance, because it does not change form and does not have volatile or insoluble forms. However, chloride is difficult to measure in highly colored water, such as lagoon liquid. Sometimes total dissolved solids are used as an indication of dilution. Dissolved solids can be measured gravimetrically, or can be estimated from measurements of conductivity. This option was also not available for us because the major dissolved substances in the water were ammonium ion and its associated bicarbonate ion. Both TAN and alkalinity increased substantially during the study, so this is not a useful substance to use as a tracer.

Total phosphorus (TP) is a relatively conservative element in wastewater lagoons and does not have a volatile form. TP concentrations were highly variable throughout the study (Figures 7 and 8). TP concentration does not typically have seasonal cycles (as does nitrogen). The slopes of the trendlines for phosphorus concentration during the study (not shown) were all negative, indicating a decrease in total phosphorus concentrations occurred during the study period. Ortho-phosphate concentrations were very similar, as ortho-phosphate was the vast majority of the TP. Since the nitrogen concentrations increased while the phosphorus concentrations decreased, it is likely that the increases in nitrogen concentrations were due mostly to increased nitrogen content of the lagoons, and not to a concentration effect from rainwater exclusion. Phosphorus concentrations are not a perfect tracer, however, and other processes could be contributing to their decrease. For example, phosphorus is frequently closely associated with particulates.

However, suspended solids concentrations slightly increased during the study, although concentrations varied widely (data not shown).

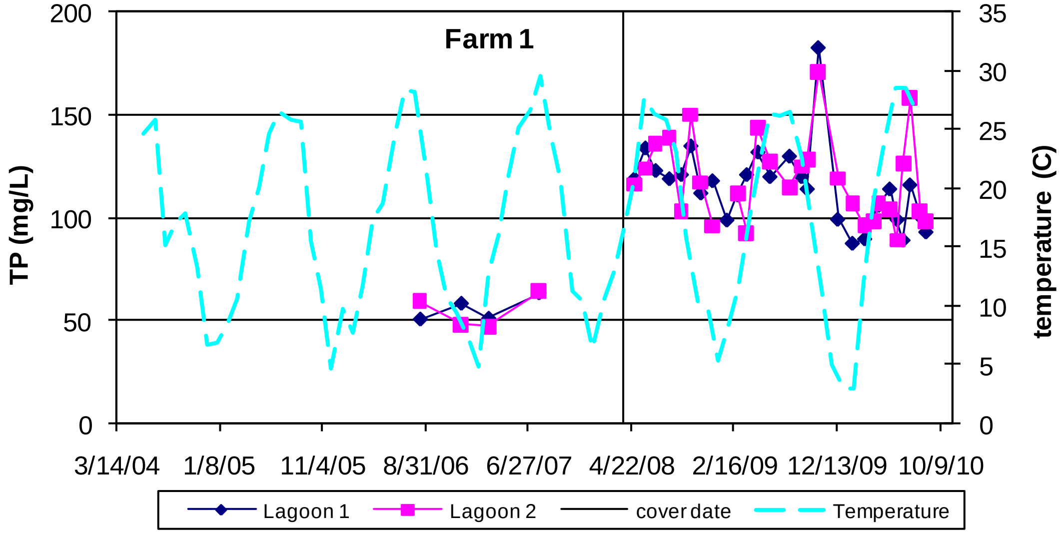

Figure 7. Total phosphorus (TP) concentrations at Farm 1(Lagoons 1 and 2).

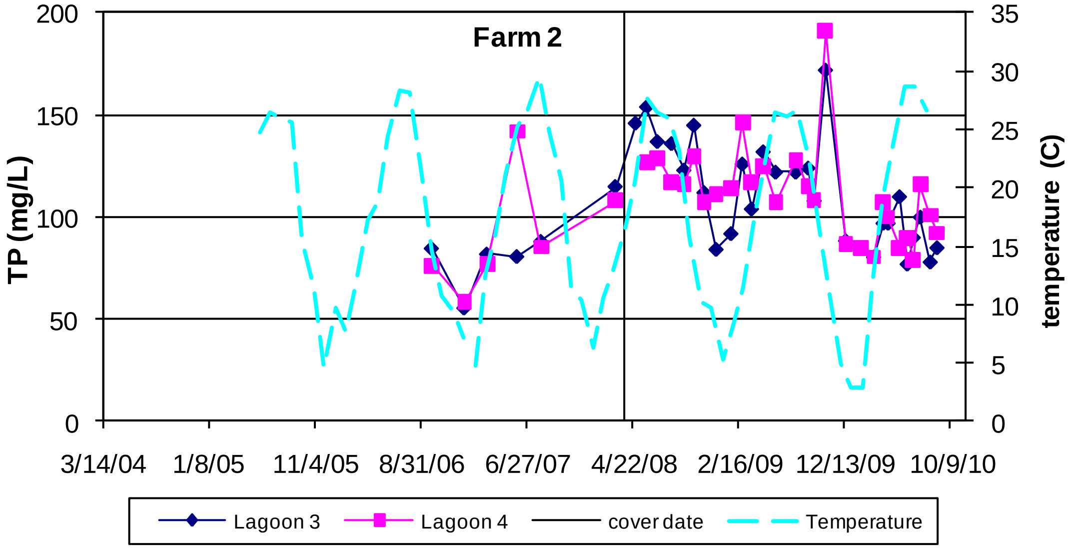

Figure 8. Total phosphorus (TP) concentrations at Farm 2 (Lagoons 3 and 4).

Mass Balance

A complete mass balance of the water and nitrogen entering and leaving the system would help to determine if the increase in nitrogen concentration truly represents an increase in the amount of nitrogen to be disposed of. We were not able to collect data to calculate a complete mass balance for the system, due largely to sampling problems caused by the covers. However, we were able to estimate nitrogen entering, leaving, and accumulating during this study on one of the study farms.

Nitrogen input to the lagoons was estimated using two different empirical calculations for nitrogen excretion, based on the number of pigs (or steady-state live weight) at the farm (ASAE, 2005; NRCS, 2010). These two methods give different results, so the two were averaged, to give 108 Mg N/year (238,000 lbs N/year).

Nitrogen output from the lagoons occurred in the forms of lagoon liquid irrigated onto crop land and ammonia present in the collected biogas. Irrigation records were kept at the farm collectively for the two lagoons, for cropping seasons. Average TN measurements for each period were used to calculate the amount of TN applied to land over the study period. Assuming equal amounts taken from the two lagoons, 18.6 Mg of nitrogen (41,100 lb N) was the estimated amount of nitrogen applied. The amount of ammonia lost in the biogas was also estimated, using biogas volumes measured in 2010 and extrapolated over the study period, and calculating an ammonia concentration in the air based on Henry's Law, using field measurements of pH, temperature, and total ammoniacal-N. The estimated loss of ammonia in the biogas was approximately 0.01 percent of the input nitrogen was not included in further calculations.

Nitrogen accumulated in the lagoons included increased concentrations in the lagoon liquid and nitrogen content of accumulated sludge. Nitrogen accumulated in the lagoon liquid was estimated using lagoon volumes and average concentrations of TN at the beginning and end of the study. The lagoon volumes were calculated based on the data (lagoon total depth and length and width measurements) from the lagoon sludge surveys conducted prior to the covers being installed. The final depth of sludge was calculated by subtracting the depth to sludge measurement obtained with a sonar unit from the lagoon total depth data from the initial sludge survey. The estimated difference in TN content of the lagoon liquid from the beginning to the end of the study was 46.6 Mg N (102,700 lb N). The amount of N in the accumulated sludge could not be measured directly. As an estimate, we considered data from Cheng et al. (2004), which was measured at a covered lagoon digester (ambient temperature) in North Carolina. Cheng found that 28 percent of the input nitrogen remained in the sludge in this digester. This situation is very similar to a lagoon with an impermeable cover, and we felt this was the best estimate we could make. Therefore, we estimated that 70.6 Mg N (155,600 lb N) was accumulated in the sludge during the 28 months of this study.

The total amount of nitrogen accounted for in output and accumulation was 136 Mg N (299,400 lb N), or 54 percent of the input nitrogen. This total includes 7.4 percent of the input N that was land applied, 28 percent of the input N that accumulated in the sludge, and 18.5 percent of the input N that accumulated in the lagoon liquid (Table 2). These numbers are fairly gross estimates; the amount of N produced in the pig waste and the amount of N accumulated in the sludge are especially likely to be somewhat inaccurate. However, this estimated balance does indicate a likelihood that there is nitrogen produced in the manure that is not accounted for and is either escaping from the system or is accumulating somewhere that is not detected. Possible leaks from the system include volatilization of ammonia through the three openings in the covers and loss of nitrogen (as ammonia or from denitrification) in the houses. Losses from the houses are likely to be much larger than losses through the cover openings, but actual measurements have not been made.

Table 2. Total Nitrogen (TN) and Total Phosphorus (TP) Estimated Mass Balances for Farm 2 During the Evaluation Period.

	Total Nitrogen (TN)			Total Phosphorus (TP)		
	Mg N	lb N	% of Estimated Input	Mg P	lb P	% of Estimated Input
Input [1]	252	555,000		54.5	120,200	
Output (irrigation)	18.6	41,100	7.4%	0.97	2,140	1.8%
Liquid Storage	46.6	102,700	18.5%	-2.21	-4,880	-4.0%
Sludge Storage [2]	70.6	155,600	28.0%	63.1	139,000	115.6%

[1] Average of input estimates from ASAE (2005) and NRCS (2010)

[2] Based on N retention in sludge estimated by Cheng et al. (2004) and measured sludge N:P of 1.118.

A balance on phosphorus (TP) was also done to compare to the nitrogen balance (Table 2). The same references were used to estimate input production from the pigs, and the same assumption of 28 percent of the nitrogen remaining in the sludge was made. To estimate the amount of TP in the sludge, we used sludge analysis data from composite samples that were collected during the last summer of the study. The average ratio of N to P in the sludge samples was 1.118 (compared to ratios in the lagoon liquid of 8.3 initially to 24.5 at the end of the study). The relative amount of P in the sludge was much higher than in the liquid. Using these estimates, the input rate was 23.4 Mg P/year (51,500 lb P/yr), the amount that was land applied was 972 Kg P (2,140 lb P), and the accumulation in the sludge was 63.1 Mg P (139,000 lb P). Phosphorus concentrations in the lagoon liquid decreased, and the negative accumulation in the lagoon liquid was -2.21 Mg P (-4,880 lb P) during the 28 months of the study. These estimates account for 113 percent of the estimated input P. Again, these estimates are not necessarily very accurate. However, since the vast majority of the P is estimated to be in the sludge, it is likely that this number is an overestimate, and thus, the sludge N accumulation may also be an overestimate.

The suggestion from this analysis is that a relatively small portion of the input nitrogen (and phosphorus) was land applied for ultimate disposal / usage. The increase in N concentration in the lagoon liquid represents an increase in the storage of N in the lagoon; this process may not have reached a steady state by the end of the study.

Summary of Nitrogen Study

Nitrogen concentrations approximately doubled in the lagoon liquid at the study sites. Some of the increase in concentration was likely due to rainfall exclusion. However, since rainfall exclusion is balanced to some extent with evaporation prevention, over time the rainfall exclusion may not have a large effect on nitrogen concentration. Rainfall exclusion is still a major benefit of lagoon covers, especially for large storm events, by preventing volume increase in the lagoon that would occur at the same time that ground is saturated.

Measurement of Sludge Depth in Covered Lagoons

Lagoon covers limit the ability to access the lagoon surface in order to survey the bottom and sludge profiles as required by the current rules. Sonar units have been used on uncovered lagoons to measure the distance from the liquid surface to the top of the sludge layer (depth-to-sludge measurement) in the lagoon and have worked well when operated either by an operator from a boat on the lagoon surface or with a remotely controlled boat. Sonar systems work by transmitting a sound wave and measuring the time it takes for the sound wave to be reflected back to the unit. The depth of the reflecting surface, in our case the sludge layer, is then calculated based on the known speed of sound in water. Therefore, it should be possible for a sonar unit to make a measurement through a lagoon cover as long as the cover material is dense enough to transmit sound waves.

Methods

To assess the potential to use sonar units to measure the distance from the top of the floating cover to the top of the sludge layer for covered lagoons, three experiments were conducted: (1) a survey of each of four covered lagoons was conducted and the results compared to surveys that were conducted just prior to the covers being installed, (2) a small, four square feet section of cover material was floated on the surface an uncovered lagoon and depth to sludge measurements taken from on top of the cover material as well as adjacent to the material, and (3) three sludge surveys were conducted on a single covered lagoon on the same day.

Experiment 1

Sludge surveys were conducted on the four lagoons in 2008 prior to the covers being installed. An operator conducted the 2008 surveys by using the sonar method and a boat on the liquid surface of the lagoon to collect and record approximately 1,200 depth-to-sludge measurements at random locations across each lagoon. The 2010 surveys were conducted by walking across the cover and placing the sonar transducer at 12-15 points across the top surface of the covers depending on the surface area of each lagoon (Westerman, et al., 2008). The distance from the maximum liquid level to the current liquid level was also measured at the time of the 2010 survey and used to calculate the distance from the current liquid level to the lagoon bottom based on similar measurements collected during the 2008 survey.

Experiment 2

In order to determine the extent that the cover material might affect the depth measurement, a four square feet section of the high-density polyethylene (HPDE) cover material was placed on the surface of an uncovered lagoon at three locations. At each location four depth-to-sludge measurements were recorded along with four measurements taken immediately adjacent to the section of HPDE material.

Experiment 3

The final experiment involved surveying a single two-acre covered lagoon three times on a single day by a single operator. The three surveys were conducted within a two-hour period.

Each survey consisted of six points along two transects of the lagoon for a total of twelve points per survey.

Results

Experiment 1

Average sludge accumulation rates of the four lagoons were substantially different (Table 3). The survey of Lagoon 1 indicated that the sludge level had decreased by 0.5 feet, while the survey of Lagoon 3 indicated an increase in the depth of sludge by 1.0 foot. Two of the covered lagoons were part of a previous sludge study conducted in 2004, and at that time surveys indicated that the lagoons had experienced a sludge accumulation rate of about 0.3 feet of sludge accumulation per year over their life span up to that point. Three of the four lagoons exhibited a rate of sludge accumulation that is similar to the accumulation rate of the previous study. The fourth lagoon, Lagoon 1, had a small amount of sludge removed just prior to the cover being installed, but after the 2008 survey, which could explain the decreased level of sludge. In addition, the limited number of depth observations for each lagoon when compared to the 2008 survey makes direct comparisons difficult.

Table 3: Comparison of Pre and Post Cover Sludge Surveys

	Average Depth of Sludge, m (feet)			
	Lagoon 1	Lagoon 2	Lagoon 3	Lagoon 4
Pre-cover survey 2008[1]	1.28 (4.2)	0.91 (3.0)	0.88 (2.9)	0.73 (2.4)
Post-Cover survey 2010[2]	1.13 (3.7)	1.04 (3.4)	1.19 (3.9)	0.79 (2.6)
range of values:	0.79-1.86		1.10-1.98	1.13-1.95
	(2.6-6.1)	(7.2-9.1)	(3.6-6.5)	(3.7-6.4)
Change in depth	-0.15 (-0.5)	0.12 (0.4)	0.30 (1.0)	0.06 (0.2)

[1] n=1,200

[2] n=14 for Lagoon 1 and 2, n=15 for Lagoon 3 and n=12 for Lagoon 4

Experiment 2

Measurements of depth to sludge were made in three locations on an uncovered lagoon, with and without cover material on the surface. The variation in individual depth measurements at each location (Table 4) is typical of sonar measurements in general and is the result of the basis on which they operate. The sound wave moves out from the transducer in a cone pattern and thus the signal can be reflected back from any point within the area of the cone. There is very little difference between the average depth-to-sludge measurements with and without cover material at the three locations (Table 4), which indicates that the cover material has little impact on the depth to sludge measurement.

Experiment 3

Three surveys of the same covered lagoon were conducted during a two-hour period. Survey 1 indicated an average depth-to-sludge of 4.0 feet while both Survey 2 and Survey 3 indicated an average depth-to-sludge of 4.2 feet (Table 5). The relatively low number of sample points may have contributed to the differences seen between Survey 1 and the other two surveys. Twelve measurements is the minimum number of measurement locations recommended for a two-acre lagoon (Westerman et al., 2008). An increased number of sample points would likely provide a better indication of the actually average depth-to-sludge measurement.

Table 4: Effect of Cover Material on Depth-to-Sludge Measurement

	Location 1		Location 2		Location 3	
	Depth to Sludge, m (ft)		Depth to Sludge, m (ft)		Depth to Sludge, m (ft)	
	without cover	with cover	without cover	with cover	without cover	with cover
	2.38 (7.8)	2.38 (7.8)	2.53 (8.3)	2.53 (8.3)	2.62 (8.6)	2.95 (8.7)
	2.38 (7.8)	2.41 (7.9)	2.50 (8.2)	2.53 (8.3)	2.59 (8.5)	2.62 (8.6)
	2.41 (7.9)	2.41 (7.9)	2.53 (8.3)	2.53 (8.3)	2.59 (8.5)	2.62 (8.6)
	2.35 (7.7)	2.38 (7.8)	2.53 (8.3)	2.53 (8.3)	2.62 (8.6)	2.62 (8.6)
Average	2.38 (7.8)	2.41 (7.9)	2.53 (8.3)	2.53 (8.3)	2.62 (8.6)	2.62 (8.6)

Table 5: Repeatability of Three Consecutive Sludge Surveys

	Depth to sludge, m (ft.)		
	Survey 1	Survey 2	Survey 3
	1.28 (4.2)	1.40 (4.6)	1.31 (4.3)
	1.19 (3.9)	1.31 (4.3)	1.25 (4.1)
	1.16 (3.8)	1.37 (4.5)	1.19 (3.9)
	1.28 (4.2)	1.43 (4.7)	1.34 (4.4)
	1.25 (4.1)	1.49 (4.9)	1.46 (4.8)
	1.13 (3.7)	1.46 (4.8)	1.25 (4.1)
	1.16 (3.8)	1.13 (3.7)	1.16 (3.8)
	1.22 (4.0)	1.28 (4.2)	1.22 (4.0)
	1.10 (3.6)	1.04 (3.4)	1.04 (3.4)
	1.49 (4.9)	1.31 (4.3)	1.40 (4.6)
	0.82 (2.7)	0.98 (3.2)	1.01 (3.3)
	1.71 (5.6)	1.28 (4.2)	1.55 (5.1)
Average	1.22 (4.0)	1.28 (4.2)	1.28 (4.2)

Summary of Sludge Study

Overall, the data suggest that the sonar method will perform adequately for measuring the depth to sludge on lagoons with HPDE covers with certain limitations. Walking on the cover to manually place the transducer in contact with the cover will cause the cover to sag under the body weight[1]. Thus the indicated measurement will be slightly less than the actual measurement. In addition, care must be taken to ensure that air is not trapped under the cover at the point of measurement. The trapped air prevents the transmission of the sound wave and is typically

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[1] Necessary precautions should be taken to ensure worker safety when walking on the lagoon covers.

indicated by error message or flashing display on the sonar unit. Sludge survey measurement averages were repeatable (Experiment 3), which indicates that for comparison purposes the sonar method should be quite adequate as long as the surveys are performed under similar conditions (similar sample locations, similar operator weight, etc.).

Options for Nitrogen Recovery from Covered Lagoon Liquid

The increase in nitrogen concentrations in covered lagoons that was observed during the monitoring phase of this project has allowed us to alert producers to the likelihood that additional nitrogen management will be required if covers are installed on existing lagoons. These results have also stimulated interest in nitrogen management techniques and, especially, in potential nitrogen recovery technologies.

Nitrogen is a fairly abundant element, but is predominantly found in the non-reactive form of nitrogen gas (N_2) in the atmosphere. Reactive nitrogen, in the forms of ammoniacal N, organic N and nitrogen oxides, is required by most living organisms and is frequently a limiting factor to plant production. Since the 1960’s, the amount of reactive nitrogen available to the biosphere has increased substantially, due in large part to development of an industrial process for production of ammonia from N_2 (from the atmosphere) and H_2 (from natural gas). This production of reactive nitrogen for fertilizer has allowed a substantial increase in food production. However, the release of large amounts of reactive nitrogen also has undesirable effects on the environment, and the production of ammoniacal nitrogen is an energy intensive process (Galloway et al., 2003; UNESCO, 2007; Gruber and Galloway, 2008). Reuse of the reactive nitrogen in animal waste is accomplished in some areas of the country by direct utilization as fertilizer on row crops. However, in North Carolina, the amount of animal waste nitrogen available frequently exceeds the suitable crop land needs, and the excess nitrogen must be applied to land that would not otherwise be cropped to avoid undesirable release to the environment. Farmers are sometimes limited in their animal production by the amount of land they have available that can be used for nitrogen application. One strategy for managing release of reactive nitrogen in the environment is to stimulate conversion back to nonreactive N_2. This process is energy intensive, and is wasteful of the reactive nitrogen that could be used beneficially. Recovery of the nitrogen in a useable form (e.g., as fertilizer) that can be readily transported off-farm is advantageous from the perspectives of energy usage, carbon footprint, environmental health, and nutrient management. Three strategies for nitrogen recovery were investigated.

ammonia stripping

One approach to recovery of ammonia from water is to use stripping technology. Ammoniacal-N is found in two forms in water: ionic ammonium (NH_4+) and ammonia gas (NH_3). The volatile form, NH_3, predominates in the higher pH range. Values of pH from 10.5 to 11.8 are generally considered to be required for ammonia stripping to be effective (USEPA, 2000). However, temperature has an important effect on stripping, as higher temperature reduces the solubility of gases in water and increases the rate of transfer into the air (Metcalf & Eddy, Inc., 2003). Increasing the temperature has been shown to greatly reduce (or eliminate) the need to increase the pH in wastewaters with high concentrations of ammonia (Collivignarelli et al., 1998; Bonmati and Flotats, 2003). Use of heat rather than pH adjustment would have a significant advantage of not requiring large amounts of caustic alkali chemicals for pH adjustment. Bench scale stripping tests conducted at the NCSU Lake Wheeler Road Facility in a 1.2 meter (4-ft) column indicated that temperature of 60-65^{o}C (140-150^{o}F) might be enough to make stripping effective without pH adjustment (Liehr et al., 2006). Further tests in a taller column were needed to provide a more realistic representation of the columns used in practice.

One challenge for stripping ammonia from water is that NH_3 is very soluble. This effect is generally described using Henry's Law:

$$P_{gas} = H * x_{liquid}$$

where P_{gas} is the partial pressure in the gas phase, x_{liquid} is the mole fraction of ammonia in water, and H is the Henry's Law Coefficient (in atm). The Henry's Law Coefficient for NH_3 is very small, indicating that concentration in the gas phase in equilibrium with the liquid phase will be small (Metcalf & Eddy, Inc., 2003). This coefficient is very dependent on temperature, and gases in general become much less soluble at higher temperatures. Therefore, increased temperature will improve the ammonia removal in a stripping column.

Another challenge of stripping ammonia from wastewaters is that all of the total ammoniacal nitrogen (TAN) is not in the volatile form, NH_3. The equilibrium between the two forms of TAN is dependent on the pH:

$$NH_4^+ \leftrightarrow NH_3 + H^+$$

The pKa for this equilibrium is 9.26 at a temperature of 25^{o}C, which means that at a pH of 9.26, half of the TAN would be in the volatile form, NH_3. To increase the amount of NH_3, the pH would have to be raised. A pH of at least 10.5 is generally considered to be required for effective ammonia stripping processes (USEPA, 2000).

Methods

A countercurrent stripping tower process was used in this research. In a countercurrent system, liquid enters at the top of the tower and clean air enters at the bottom (Figure 9). The air exiting the reactor at the top is in contact with the highest concentration in the liquid, and therefore has the highest equilibrium concentration of NH_3. The liquid exiting the reactor at the bottom of the column is in contact with the cleanest air, and will therefore have the lowest equilibrium concentration in the liquid (Metcalf & Eddy, Inc., 2003).

The reactor used in this research was a PVC column of 0.30 m (12 in) diameter and 6.1 m (20 ft) height, packed with Jaeger Tri-Packs® plastic media. Packing that was used in this reactor had a diameter of 2.5 cm (1 in) with the following characteristics: surface area of 280 m^2/m^3 (85 ft^2/ft^3), bulk density of 99 kg/m^3 (6.2 lb/ft^3), and void volume of 0.90. Sample ports were located at 1.5 m (5 ft) intervals along the column.

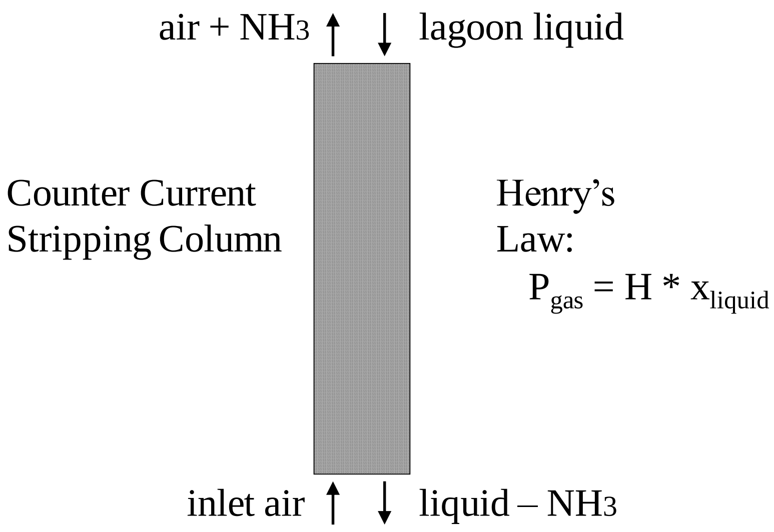

Figure 9. Schematic diagram of a counter-current stripping column.

In the current study, tests were done using air and liquid temperatures greater than ambient temperature. In practice, heat can be obtained from burning the collected methane, but in our tests, conducted at the NCSU Lake Wheeler Road Facility, we utilized available energy sources (electricity or propane). In the initial test, lagoon liquid was heated to 55^{o}C (130^{o}F) and then was pumped to the stripping tower. However, the air used for stripping was not heated, and excessive heat loss occurred in the column. Subsequent tests were done using air heated to approximately 74^{o}C (165^{o}F) and liquid heated to 57^{o}C (135^{o}F). The initial pH of the liquid was 7.8 (at the heated temperature). The liquid flow rate varied between 3.6 – 7.4 L/min (1 – 2 gal/min), and the ratio of air flow to liquid flow (G:L) ranged from 520 to 1300.

Results

We tested the ammonia stripping process with lagoon liquid that had reached a concentration close to the eventual maximum. Average characteristics of the liquid tested were the following: TKN=2,420 mg/L; TAN=2,130; alkalinity=11,100 mg/L as $CaCO_3$; TP=118 mg/L. The average temperature of the liquid in the column was 41^{o}C (106^{o}F). Significant cooling of the liquid occurred, even though the air stream was heated to a hotter temperature than the liquid, due to evaporative cooling and lack of insulation on the column. Ammonia removals generally increased with increased relative air flow (i.e., increased G:L), although we did not observe a removal greater than 19 percent (Figure 10).

The average temperatures achieved in the stripping column (approximately 41^{o}C) were not high enough to result in adequate ammonia removal. Previous bench scale stripping tests indicated that temperature of 60-65^{o}C (140-150^{o}F) might be enough to make stripping effective without pH adjustment (Liehr et al., 2006), but we did not reach that temperature.

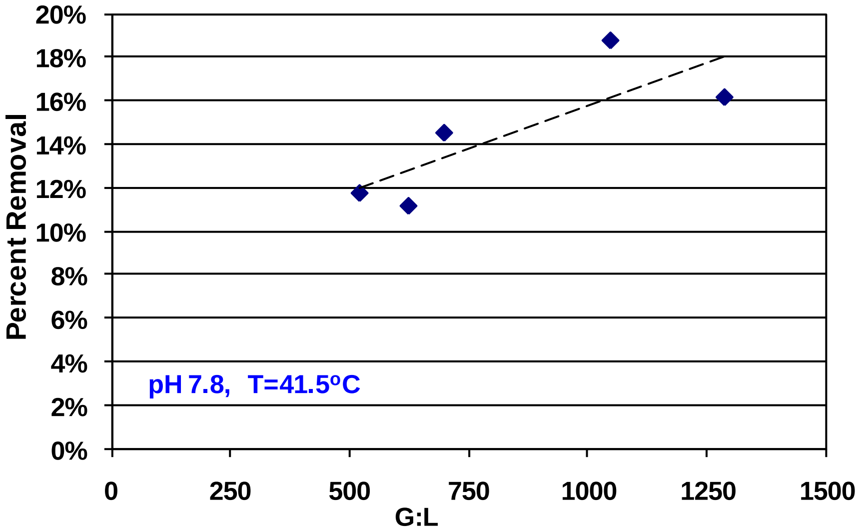

Figure 10. Percent removal of ammonia nitrogen (TAN) in a stripping column in relation to gas-to-liquid volume ratio (G:L).

Tests had been conducted previously with the same column (20-ft) using liquid from a lagoon with a permeable cover (from Onslow County, NC), which has characteristics intermediate to typical lagoon liquid and the lagoon liquid we have observed in this study. These tests were designed to look at pH adjustment and various air flow rates as factors for optimizing stripping potential. In this study, at a temperature of 32°C (90°F), when pH was raised so that 75% of the total ammonia (TAN) was in the form of NH_3, a G:L ratio of 1000 was projected to be adequate to remove 50% of the TAN. However, a large amount of caustic alkali chemicals were required to increase the pH of this well-buffered waste stream. Hydrated lime ($Ca(OH)_2$) was the alkali chemical used; 6,000 mg/L (5 lb per 100 gal) was needed to reach this pH. The amount needed would be even greater for the covered lagoon liquid of the current study due to the higher ammonium ion and alkalinity concentrations, which greatly increase the buffer capacity. Based on these higher concentrations, a lime dose of approximately 10,800 mg/L (9 lb per 100 gal) would be required to reach the equivalent pH in this liquid. This dose of lime would mean adding 5,800 mg/L of calcium to the liquid, which could cause scaling, especially in the heated pipes. If the alkali was added as lye (NaOH), this dose would mean adding 6,700 mg/L of sodium (Na). This level of salts addition could affect treated water disposal options.

The best option would likely be a moderate pH increase in addition to temperature increase. High temperature could be achieved relatively cheaply in this application by using heat from the collected methane (which was being flared at the time of this study). The second step of the recovery, acid scrubbing of the ammonia from the air, will also require handling of chemicals. This stage of the process was not explored in this study.

membrane separation technology.

Membrane separation can also be used to remove (and recover) dissolved substances such as ammonia from water. Reverse osmosis (RO) is a membrane technology that uses semi-permeable membranes that allow water to pass through, but are not permeable to dissolved substances. Separation occurs when water is forced through the membrane by applying pressure, leaving the dissolved substances on the other side of the membrane. Many advances have been made in this technology to reduce problems from fouling of the membranes. Typical applications include water treatment and desalination, where the main treatment challenge is the removal of dissolved components. In these cases, the goal is to produce good quality water rather than to recover the substances in the water. This technology has also been applied to various types of industrial and food processing wastes, but has not been applied to swine lagoon wastewater. Application of RO technologies to swine wastewater will be challenging due to its nature and composition. Considerable pretreatment would be required to prevent fouling of the membranes. The fine particulates that are characteristic of swine wastewater are especially difficult, and important, to remove.

A different type of membrane technique, using gas permeable membranes, is being developed and tested by USDA-ARS (Vanotti and Szogi, 2010). Gaseous ammonia (NH_3) passes through the submersed membrane. Dilute acid on the other side of the membrane traps and collects the NH_3. Tests were done using tubular membranes with liquid swine manure containing approximately 1500 mg/L TAN. Dilute acid (pH < 1-2)was circulated through the tubes. Most of the free ammonia (unionized NH_3) was removed from the manure liquid and was recovered in the acid. However since most of the TAN is typically in the form of ionized ammonium (NH_4^+), this is not an efficient method for removing and recovering nitrogen. Vanotti and Szogi (2010) also tested removal after increasing the pH to 9 – 12 with strong base (alkali) addition. Increased pH greatly improved N removal and recovery, resulting in greater N removal and higher N concentration in the recovery acid. However, utilizing high pH followed by acid recovery has the same problem as ammonia stripping through towers. This process would require a lot of strong base and acid solution to recover a significant portion of the nitrogen. It is not yet known if this process would be more or less efficient than a stripping tower followed by an acid scrubbing tower.

algal growth for biodiesel production

One way of utilizing the nutrients in lagoon liquid is to grow algae for use in biodiesel production. Algae are photosynthetic organisms that convert water, CO_2, light, and nutrients into biomass. This is an extremely diverse group of organisms. Some types of algae produce lipids (oils) as storage products. These oils can be recovered and used to produce biodiesel fuel.

Early researchers in production of biodiesel from algae found the technology to be very promising, but expensive (Sheehan et al., 1998). Projections have been made that oil production per acre from algae could exceed oil from soybeans by a factor of 100 or more, although this projection has not been confirmed in practice. Algae are attractive because they are fast growing, they do not compete with food crops, and they can be grown on marginal land using freshwater or saltwater. This area has attracted funding interest from a number of prominent sources, including the US Department of Energy, ExxonMobil, Ford Motor Company, and Bill Gates. A number of start-up companies have sprung up to explore the options.

A major environmental expense of algae production is provision of nutrients (N and P) and CO2. Atmospheric CO2 is generally not adequate to maintain optimal algal growth rates. One especially promising approach to growing algae economically is to locate the production close to sources of recycled nutrients and CO_2, such as near wastewater treatment facilities (for nutrients) or power generating facilities (for CO_2) (Clarens et al, 2010). Swine farms with covered lagoons could potentially provide both of these conditions. Lagoon liquid might be effective as a nutrient source, and supplemental carbon dioxide for algal growth stimulation could be supplied from burning of collected methane.

Although algae biofuels are stimulating a lot of interest, much more work needs to be done before this will be a feasible technology. The simplest application would be to grow mixed native communities of algae in open pond-type structures. However, there are a number of issues with this approach. Some types of algae are much more desirable as biofuel sources than others, and growing them in open ponds does not allow the level of environmental control necessary to maintain those species as the dominant member of the algal community. Most studies currently being conducted are using species that are genetically modified to produce oils. A large component of the research is in development of closed engineered bioreactors that allow control of environmental factors while preventing contamination from natural species of algae and other organisms. Optimal conditions for growing the desirable algae with maximum production of oil are not yet established. Processing procedures for turning the algae into biodiesel, or other biofuel, are also in development stages.

The potential for growing oil-producing algae with high-nutrient swine lagoon liquid is currently unknown; we do not yet know what species of algae or what growing techniques will be required. This may become a more attractive alternative as the state of knowledge becomes better established. Collecting the biofuel portion of the algae will not actually result in nutrient utilization, however, as these techniques become better established, techniques for processing the remaining biomass into feed or fertilizer will also be developed.

Summary of Nitrogen Recovery Evaluation

The three approaches to nitrogen recovery that were investigated all have problems in terms of immediate application to swine farms in North Carolina. These technologies have not been extensively tested for swine waste treatment, and may be expensive and management intensive. However, ammonia fertilizer is also becoming expensive, and high costs may mean that more expensive recovery technologies could become feasible.

Carbon Footprint of Swine Production in North Carolina

The term “carbon footprint” is frequently used to refer to the impact that a given activity has on greenhouse gas emissions. Greenhouse gas (GHG) emissions have become an important topic in the US. One of the benefits of placing a cover over swine lagoons is the elimination of methane (CH_4), a greenhouse gas, and the possible use of the methane to generate power that would otherwise be generated using fossil fuels, creating the greenhouse gas CO_2. There may also be GHG emission benefits from preventing ammonia volatilization and recovery and reuse of nitrogen. This is a complex topic and requires that we try to put it in perspective.

The three main greenhouse gases that pertain to agriculture are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Carbon dioxide emissions are not considered to be a GHG emission if they are part of the normal pool of the carbon cycle. CO_2 is generated from the natural gas that is used in the Haber-Bosch process for making nitrogen fertilizer from atmospheric N_2. CO_2 is also released as a result of some land-use changes, such as deforestation. Methane is a more potent GHG than CO_2, and is generally considered to have approximately 21 times the greenhouse effect. The main sources of methane in animal agriculture are anaerobic decomposition of manure and enteric fermentation by ruminant animals (cattle, sheep and goats). Pigs are not ruminants and do not produce significant methane in their digestive systems. Nitrous oxide is even more potent as a GHG than methane, with approximately 296 times the greenhouse effect of CO_2. N_2O is an intermediate product of denitrification and can be released in the process of conversion of ammonia (in fertilizers or manure) to nitrate to N_2. N_2O is not usually the major product of this conversion, but the amount varies with different environmental conditions. The first step, conversion of ammonia to nitrate, requires oxygen to be present, so this is not thought to be a major product of anaerobic manure storage. Since the different GHG components have different effects on greenhouse effects, emissions of these components are generally given as CO_2-equivalents, giving an indication of greenhouse effect rather than actual concentration.

Considerable concern regarding GHG emissions from animal agriculture has been raised as a result of a United Nations report in 2006 (FAO, 2006). Reports from other organizations, including the USEPA (2010) seem to contradict the FAO report. Part of this difference results from including different components in the analysis. Pitesky et al. (2010) analyzed these reports to compare inclusion of various indirect effects such as feed production, fertilizer production, transportation of materials and equipment, etc. It is useful to look at these components to determine which ones actually apply to swine farms.

The FAO (2006) report states that animal agriculture accounts for 18% of the global GHG emissions. The FAO report breaks down the sources attributed to animal agriculture as follows:

CO_2 sources:
- Deforestation 34%
- Other land use 2%
- Fertilizer production, fuel use on-farm, processing, transport 2%

CH_4 sources:
- Enteric fermentation 25%
- Manure management 6%

N_2O sources:
- Manure management, direct and indirect 25%
- Fertilizer 3%
- Leguminous feed cropping 3%

It is easy to see that some of the major categories do not apply to our swine farms. Deforestation accounts for more than one-third of GHG emissions globally; this is not an issue in the US. Most of the deforestation cited by this report occurred in Latin America and parts of Asia. Enteric fermentation is also a large component; this is a concern is the US but not for swine farms.

The USEPA (2010) reported a similar analysis for the US with very different numbers. The USEPA determined that approximately 6% of the US GHG emissions resulted from agriculture, and about half of that was attributable to animal agriculture. Key categories of emissions included enteric fermentation, 33%; manure management, 14.5%; and agricultural soil management, 50.5% (including manure application). Although swine farms do not contribute significantly to enteric fermentation emissions, they do consume a large fraction of animal feed grown on arable land, and therefore are responsible for a large fraction of emissions associated with cropland (Pitesky, et al., 2010).

The major sources of GHG emissions from swine farms are from methane produced in anaerobic storage structures, including in-house pits and flushing structures, and from N_2O produced from land application of manure or from partially aerobic treatment of manure before land application. There could also be significant N_2O formed from ammonia that volatizes from lagoons and is subsequently deposited on land or water. The most obvious benefit of lagoon covers for GHG emission reduction is the collection and destruction of methane. This could have a double benefit if the methane if then used to generate power that would have otherwise been generated with fossil fuels. The collection and measurement of methane from the study lagoons was not a part of our study; this information should be available in the future from the ECC study that installed the covers. However, methane emission reduction is estimated to be 50-75% with use of anaerobic digester-type structures (Pitesky, et al., 2010; AgStar, 2002).

The benefit of lagoon covers in reducing ultimate N_2O emissions is more difficult to determine. Our data show that ammonia volatilization is greatly reduced, retaining more of the ammonia in the lagoon liquid. If this lagoon liquid is land applied for disposal on the farm, there would not likely be a big difference in N_2O emissions compared to the typical lagoon situation. If the lagoon liquid is applied on the farm in place of fertilizer, then CO_2 emissions from fertilizer production and transport would be saved. If the nitrogen was recovered and transported off-farm for fertilizer use, again fertilizer production emissions would be saved, but some energy use in the recovery process might off-set this savings. If the additional nitrogen content of the lagoon liquid required some nitrogen removal treatment process before land application, then there would be no benefit of the additional fertilizer plus the energy cost (and associated CO_2 emissions) required of the treatment process. In addition, if the treatment system includes a nitrification / denitrification process, N_2O could be produced and released. It should not be assumed that treatment of lagoon liquid prior to land application will be a benefit for the carbon footprint.

Summary of Carbon Footprint Discussion

The technology of lagoon covers will likely have a beneficial effect on reducing carbon footprint of swine farms in North Carolina, due primarily to methane collection and to subsequent energy production from the methane. Nitrogen recovery from the lagoon could have a lesser beneficial effect, but the magnitude of this possible benefit is not clear. However, there are additional benefits of concentrating and recycling nitrogen as fertilizer for the environment: saving energy from production of fertilizers, preventing nitrogen from entering the atmosphere as ammonia and aerosols, and reducing potential for nitrogen to enter waterways.

Summary

Nitrogen content of the four covered swine lagoons increased substantially during this evaluation. At the end of the study (28 months), concentrations appeared to still be slowly increasing. Additional nitrogen management will likely be required for most farms using these covers. With the higher concentration of nitrogen in the lagoon liquid, recovery of reactive nitrogen (rather than destruction or dispersion) may become energetically and economically favorable. Although the technologies for nitrogen recovery discussed are not currently feasible, evaluation of possible options for nitrogen recovery from covered lagoon liquid should continue.

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