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Characterizing Ammonia Emissions from Swine Farms in Eastern North Carolina: Part 2—Potential Environmentally Superior Technologies for Waste Treatment

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ABSTRACT

The need for developing environmentally superior and sustainable solutions for managing the animal waste at commercial swine farms in eastern North Carolina has been recognized in recent years. Program OPEN (Odor, Pathogens, and Emissions of Nitrogen), funded by the North Carolina State University Animal and Poultry Waste Management Center (APWMC), was initiated and charged with the evaluation of potential environmentally superior technologies (ESTs) that have been developed and implemented at selected swine farms or facilities. The OPEN program has demonstrated the effectiveness of a new paradigm for policy-relevant environmental research related to North Carolina's animal waste management programs. This new paradigm is based on a commitment to improve scientific understanding associated with a wide array of environmental issues (i.e., issues related to the movement of N from animal waste into air, water, and soil media; the transmission of odor and odorants; disease-transmitting vectors; and airborne pathogens). The primary focus of this paper is on emissions of ammonia (NH_3) from some potential ESTs that were being evaluated at full-scale swine facilities. During 2-week-long periods in two different seasons (warm and cold), NH_3 fluxes from water-holding structures and NH_3 emissions from animal houses or barns were measured at six potential EST sites: (1) Barham farm—in-ground ambient temperature anaerobic digester/energy recovery/greenhouse vegetable production system; (2) BOC #93 farm—upflow biofiltration system—EKOKAN ; (3) Carrolls farm—aerobic blanket system—ISSUES-ABS; (4) Corbett #1 farm—solids separation/gasification for energy and ash recovery centralized system—BEST; (5) Corbett #2 farm—solid separation/reciprocating water technology—ReCip; and (6) Vestal farm—Recycling of Nutrient, Energy and Water System—ISSUES-RENEW. The ESTs were compared with similar measurements made at two conventional lagoon and spray technology (LST) farms (Moore farm and Stokes farm). A flow-through dynamic chamber system and two sets of open-path Fourier transform infrared (OP-FTIR) spectrometers measured NH_3 fluxes continuously from water-holding structures and emissions from housing units at the EST and conventional LST sites. A statistical-observational model for lagoon NH_3 flux was developed using a multiple linear regression analysis of 15-min averaged NH_3 flux data against the relevant environmental parameters measured at the two conventional farms during two different seasons of the year. This was used to

IMPLICATIONS

Current estimates indicate that atmospheric NH_3 emitted from North Carolina swine facilities account for approximately 46% of the state's atmospheric NH_3 emission. As part of an agreement between the state of North Carolina and two animal production agriculture companies, some potential ESTs were evaluated for NH_3 emissions. This paper describes the evaluation of six potential ESTs using the statistical-observational model developed for NH_3 emissions from the conventional LST currently in use for managing swine waste. The evaluated alternative technologies may require additional technical modifications to be qualified as unconditional ESTs relative to NH_3 emissions reductions.

compare the water-holding structures at ESTs with those from lagoons at conventional sites under similar environmental conditions. Percentage reductions in NH_3 emissions from different components of each potential EST, as well as the whole farm on which the EST was located were evaluated from the estimated emissions from water-holding structures, barns, etc., all normalized by the appropriate nitrogen excretion rate at the potential EST farm, as well as from the appropriate conventional farm. This study showed that ammonia emissions were reduced by all but one potential EST for both experimental periods. However, on the basis of our evaluation results and analysis and available information in the scientific literature, the evaluated alternative technologies may require additional technical modifications to be qualified as unconditional ESTs relative to NH_3 emissions reductions.

INTRODUCTION

The scientific attention given to atmospheric ammonia (NH_3) and its roles in both atmospheric chemistry and eutrophication of ecosystems has grown during the last decade.[1–7] It has been recognized that NH_3 is responsible for neutralizing the acids produced by the oxidation of sulfur (S) and nitrogen (N). This neutralization process results in the formation of atmospheric aerosol containing ammonium (NH_4^+), which may be of concern in increasing fine particulate matter concentration.[8–12] Swine farms are a significant source of NH_3 in eastern North Carolina. Lagoon and spray technology (LST) is the conventional and current system used in North Carolina to manage swine waste. It consists of anaerobic lagoons that store and biologically treat the swine waste (~98% liquid), and the effluent from these lagoons is periodically pumped and sprayed as a nutrient source on surrounding crop fields.[1] Many sensitive ecosystems lie within approximately 100 km of NH_3 area sources in North Carolina. Ecosystems in proximity to high NH_3 emission sources and NH_3/NH_4^+ deposition are subject to potential environmental consequences, including aquatic eutrophication and soil acidification.

The need for developing environmentally superior and sustainable solutions for the management of animal waste is vital for the future of animal farms in North Carolina, the United States, and the world. In addressing that need, the North Carolina Attorney General initiated the development, implementation, and evaluation of environmentally superior swine waste management technologies (ESTs) that would be appropriate to each category of swine farms in North Carolina. This evaluation was done through agreements between the Attorney General of North Carolina with Smithfield Foods, Inc. and Premium Standard Farm, Inc. Those agreements provided funds for research to develop and evaluate ESTs through the Animal and Poultry Waste Management Center (APWMC) at North Carolina State University, Raleigh, NC.[13] The agreements define "Environmentally Superior Technology or Technologies" as any technology, or combination of technologies that (1) is permittable by the appropriate governmental authority; (2) is determined to be technically, operationally, and economically feasible for an identified category or categories of farms (to be described in a technology determination); and (3) meets the following performance standards:

- Eliminates the discharge of animal waste to surface waters and groundwater through direct discharge, seepage, or runoff;
- Substantially eliminates atmospheric emission of NH_3;
- Substantially eliminates the emission of odor that is detectable beyond the boundaries of the parcel or tract of land on which the swine farm is located;
- Substantially eliminates the release of disease-transmitting vectors and airborne pathogens; and
- Substantially eliminates nutrient and heavy metal contamination of soil and groundwater.

Program OPEN (Odor, Pathogens, and Emissions of Nitrogen) was initiated as an integrated study of the emissions of NH_3, odor and odorants, and pathogens from potential ESTs for swine facilities. Its main purpose was to evaluate potential ESTs that have been developed and implemented under an agreement between the North Carolina Attorney General and the participating companies that own approximately 10% of the swine farms in North Carolina, using the conventional LST. Under this program, ESTs implemented at selected swine facilities were evaluated to determine if they would be able to substantially reduce atmospheric emissions of NH_3, odor, and pathogens. This study focuses on the emissions of N in the form of NH_3 from different components/processes involved in swine waste handling and treatment, including waste storage lagoons, swine houses, and spray fields at six selected EST sites. These are described below in the following format: name of the farm where the potential EST was used, type of technology, and brand name where applicable.

(1) Barham farm: in-ground ambient temperature anaerobic digester/energy recovery/greenhouse vegetable production system;
(2) BOC #93 farm: upflow biofiltration system—EKOKAN;
(3) Carrolls farm: aerobic blanket system—ISSUES-ABS;
(4) Corbett #1 farm: solids separation/gasification for energy and ash recovery centralized system—BEST;
(5) Corbett #2 farm: solid separation/reciprocating water technology—ReCip;
(6) Vestal farm: Recycling of Nutrient, Energy and Water System—ISSUES-RENEW.

These potential ESTs were evaluated during two seasons (cool and warm), and the results are compared and contrasted with data from two conventional LST swine farms (Moore farm and Stokes farm), which have been described in the companion paper.[1] The evaluation of two other potential ESTs, qualified as unconditional ESTs relative to NH_3 emissions reductions, are described in another paper.[14]

NH_3 fluxes from water-holding structures and other area sources and NH_3 emissions from animal houses at all of the ESTs and conventional farms were measured by a dynamic flow-through chamber system and open-path Fourier transform infrared (OP-FTIR) spectroscopy.

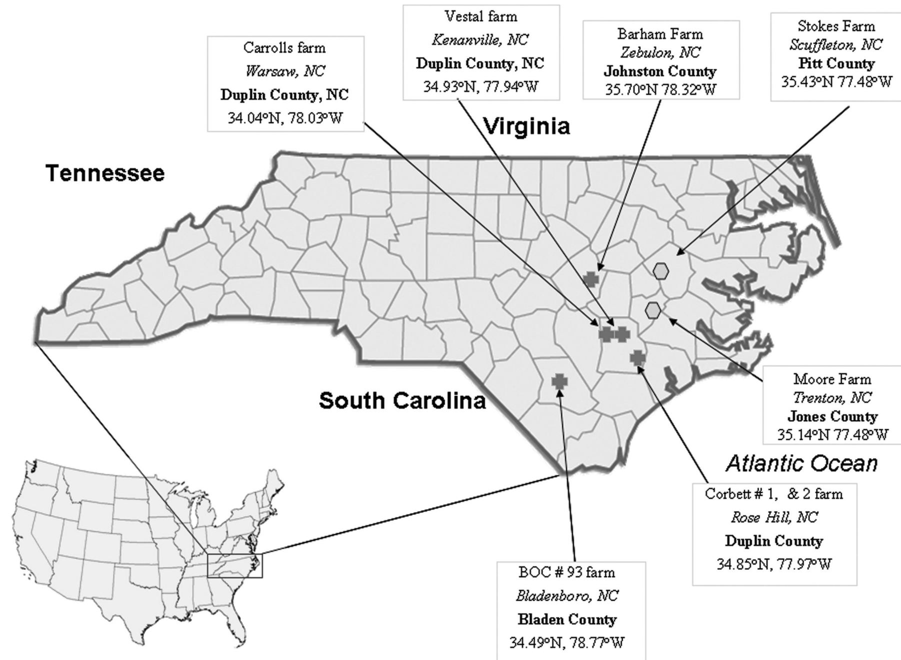

Figure 1. Map of North Carolina indicating the location of the ESTs and LSTs.

Recent studies, using a mass balance approach to estimate NH_3 emission rates, found that swine houses represent a more significant source than previously hypothesized.[15] On the basis of a review of published data, the loss of NH_3 from swine houses was estimated to be around 15% of total N excreted.[16] Griffing et al.[17] used the mass balance method to estimate that approximately 80% of NH_3 loss was due to volatilization from liquid waste storage systems. In this study also, the mass balance approach was used to estimate NH_3-N emissions from different components of the EST and LST farms, as well as N excretion rates, on the basis of swine population and feed data. Normalizing emissions by N excretion rate, percentage reductions in NH_3-N emissions are determined for water-holding structures, barns, and the whole farm for each EST facility from their estimated values for the appropriate LST farm.[1]

EXPERIMENTAL SETUPS AT EST SITES

Sampling Sites and Periods

NH_3 flux measurements were conducted during two different seasons (warm and cool) at eight swine farms (two conventional sites and six EST sites) in eastern North Carolina (for location see Figure 1). Two conventional sites (Stokes farm and Moore farm, i.e., LSTs) are also referred to as "baseline" sites for comparison with EST sites. The six EST sites were Barham, BOC #93, Carrolls, Corbett #1, Corbett #2, and Vestal farms, respectively. Aneja et al.[1] have given a detailed description of the two baseline farms with LST, as well as instrumentation and sampling techniques and scheme, therefore this information will not be repeated.

OP-FTIR measurements were conducted to measure the NH_3 flux from the ventilation systems at the swine houses. Of the swine houses measured, there were two different types of ventilation systems, namely, mechanical or tunnel ventilation and natural ventilation. At the Barham, BOC #93, and Carrolls farms, mechanical ventilation was used. At the Corbett #1 and #2 farms and the Vestal farm, the swine houses had natural ventilation. The methodologies for the measurement of NH_3-N emissions from the swine barns are described in Aneja et al.[1]

A brief description of each of the potential ESTs that have been evaluated is provided here. Williams,[18] and Williams,[19] contain more detailed information including site plans, design schematics, and projected operational characteristics.

Barham Farm. Barham Farm (35.70 °N, 78.32 °W, 130 m mean sea level [MSL]) is located near Zebulon, NC, in Johnston county. Field campaigns were conducted during April 1–12, 2002 and November 11–22, 2002, at this farm site. However, during the first measurement period in April we were notified that the EST was not fully functioning as designed, because the biofilters were not operational during that time. A schematic layout of the EST at Barham farm including the various sampling locations is given in Figure 2. This potential EST has an in-ground ambient digester comprised of a covered anaerobic waste lagoon. The primary lagoon was covered by an impermeable layer of 40-mm thick high-density polypropylene that prevented gaseous methane and other gases and odor from escaping into the atmosphere during the digestion process. Methane gas that is produced during the digestive process was extracted and burned into a biogas generator to produce electricity. Heat from the generator was captured and used to produce hot water that was used by the farm in its production activities. Effluent from the digester (covered lagoon) flowed into a storage pond with a surface area of 4459 m^2. This storage pond was formerly part of the primary anaerobic lagoon before the digester was built. A portion of this effluent was further treated via biofilters, the purpose of which was to convert NH_4^+ to nitrate in the effluent. This nitrified effluent was then used to flush out the swine production facilities, and the

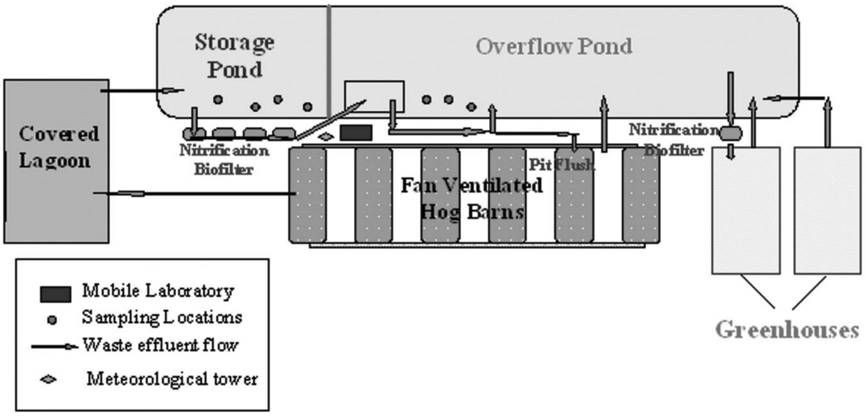

Figure 2. A schematic layout of the EST at Barham farm.

excess effluent was channeled into the larger overflow pond with a surface area of 19,398 m^2. A heavy polymer baffle separated the overflow and storage ponds. The overflow pond was used to store rainwater and overspills from the storage pond. Water from the overflow pond was also pumped into a nitrification biofiltration system where the nutrients in the treated effluent were used to fertilize vegetables grown in greenhouses adjacent to the swine production facility.

In this study NH_3 flux measurements were made from the surfaces of the storage pond, the overflow pond, and from the covered anaerobic primary lagoon. Average NH_3 concentrations were measured using the OP-FTIR spectroscopy system across the forced ventilation fan openings, as well as along the sides of swine houses (barns) to estimate barn emissions during the experimental periods.

BOC #93 Farm. BOC #93 farm (34.49 °N, 78.77 °W) is located near Bladenboro, NC, in Bladen county. NH_3 measurements were conducted on March 31, April 11, 2003, and June 16–27, 2003. A schematic layout of the EST at BOC #93 farm including the various sampling points is given in Figure 3.

The EKOKAN waste treatment system consisted of solids/liquid separation and biofiltration of the liquid with upflow aerated biological filters. Five finishing barns were connected to the waste treatment system, and the barn pits were emptied automatically in sequence. Wastewater from the barn pits was released to a solids separation unit. Coarse solids were separated from the wastewater using a screen separator (TR separator). After the solids/liquid separation process, the liquid was pumped to a 40,000-gal equalization tank. Liquid flowed from the equalization tank by gravity and passed through first- and second-stage aerated biofilters connected in series (two sets). Wastewater flowed upward through the biofilters, and air was supplied at the bottom of each biofilter with blowers. The biofilter tanks were covered, and air and any excess foam from the aerated treatment were routed through polyvinyl chloride pipes to exit points over an anaerobic lagoon. The biofilters were backwashed periodically to remove excess biosolids. Treated effluent from the biofilters flowed by gravity to a storage basin, with a portion of the treated effluent being recycled to the solids separation basin, from which it was pumped to the equalization tank, which had a surface area of 28.3 m^2. Water was pumped from the storage basin to the barns to refill the pits. At this site, the anaerobic lagoon that received manure from 10 barns was partitioned using plastic curtains into three sections, with one section much larger than the other two. The larger section received manure from five barns not connected to the EKOKAN treatment system. One of the smaller sections received any overflow from the solids separation basin, the separated solids, and

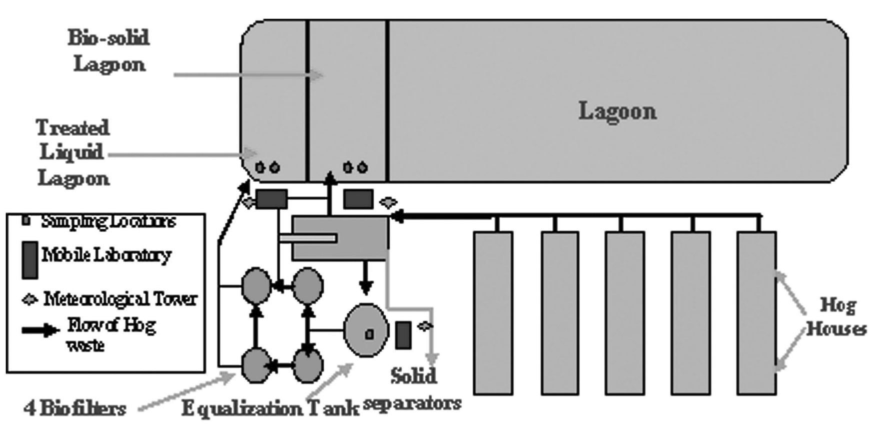

Figure 3. A schematic layout of the potential EST at BOC #93 farm.

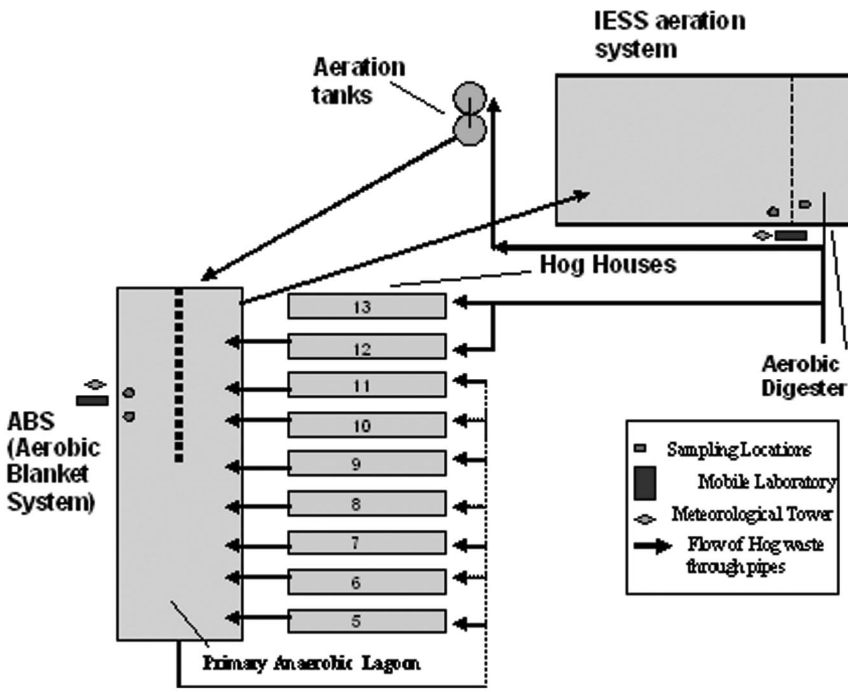

Figure 4. A schematic layout of the potential EST at Carrolls farm.

the backwashed biosolids that were removed from the biofilters. This was known as the biosolids lagoon and had a surface area of 3229.2 m^2. The other small section received the treated effluent from the biofilters. This was known as the treated effluent lagoon and had a surface area of 1614.6 m^2. NH_3 fluxes were measured from the treated effluent storage, the biosolids storage lagoon, and the equalization tank during the experimental periods.

Carrolls Farm. Carrolls (34.04 °N, 78.03 °W) is located near Warsaw, NC, in Duplin county. NH_3 flux measurements were conducted on this farm from March 29 to April 2, 2004 and from June 28 to July 2, 2004, respectively. A schematic layout of the EST at Carrolls farm including the various sampling points is given in Figure 4.

The waste stream in the proposed EST flows from the houses to a primary anaerobic lagoon equipped with the ABS. This is known as the ABS lagoon and has a surface area of 3304.8 m^2.

The ABS consists of a fine mist of treated swine waste that is applied every 15 min to the surface of the anaerobic lagoon. During both evaluation periods, only half of the anaerobic lagoon was being treated by the ABS. The treated swine waste arises from an aeration treatment that takes place in an adjoining water-holding structure (aerobic digester). Waste from the anaerobic lagoon flows into an aerobic digester (IESS aeration system). This is referred to as the west side of the aerated lagoon and has a surface area of 5068.8 m^2. This portion of the basin is sectioned off with a plastic barrier. The aerated waste eventually flows into the sectioned-off portion of the aeration treatment basin. This is known as the east side of the aerated lagoon, and has a surface area of 6010.2 m^2. The waste is then used to flush the animal houses and supplies the treated water for the ABS. During the first evaluation period, the IESS aeration system was not functioning and treated waste for the ABS was derived by using two aeration treatment tanks. For the second evaluation, the aeration treatment basin was operating as designed. Only waste from finishing houses 5–13 flowed into the ABS-equipped anaerobic lagoon. Waste from the remaining farrow and weaning houses flowed into a separate lagoon. These houses and their accompanying lagoon were not included in the evaluation of the EST.

Corbett #1 Farm. Corbett #1 farm (34.85 °N, 77.97 °W) is located near Rose Hill, NC, in Duplin county. NH_3 flux measurements were conducted during October 1–8, 2003, and December 4–7, 2003, respectively. A schematic layout of the EST at Corbett #1 farm including the various sampling points is given in Figure 5.

Manure flushed from the barns flows first to a collection pit, then to an aboveground feed tank, and then to a screw-press separator on a raised platform. The separator has a screen with 0.25-mm openings. The liquid that flows through the screw-press separator screen flows to a second feed tank, which has a surface area of 27.1 m^2, and then to two tangential-flow gravity settling tanks sited parallel to each other. Each tangential-flow settling system consists of a 2.2-m diameter tank with a cone bottom followed by a 1.2-m diameter sludge thickening tank, also with a cone bottom. Tangential flow in the first tank causes solids to concentrate in the center of the tank and settle down to the bottom. This settled slurry is then pumped to the second tank for sludge thickening. For approximately 10 min every hour the settled slurry from the second tangential-flow settling tank is pumped back to the tank that feeds the screw-press separator, where the settled slurry is combined with the flushed manure that is being pumped to the screw-press separator. The treated

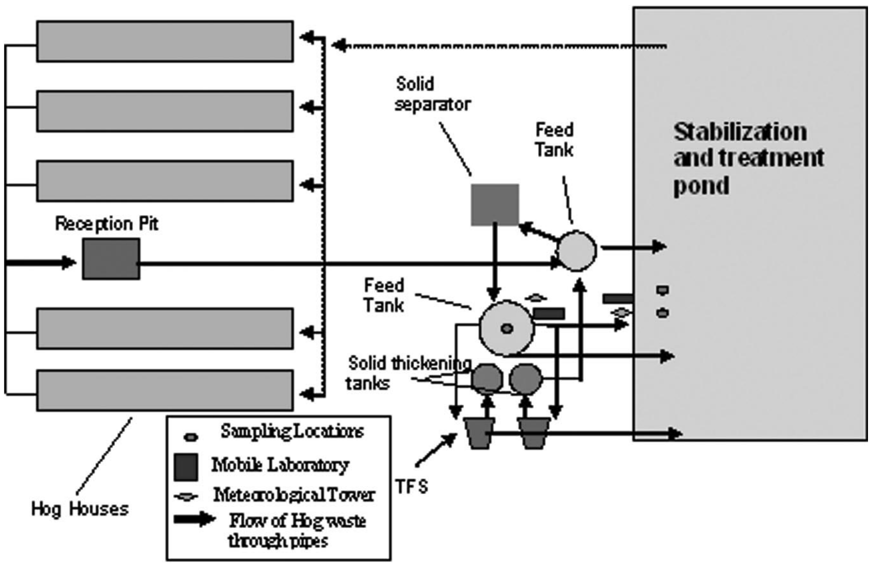

Figure 5. A schematic layout of the potential EST at Corbett #1 farm.

waste and any overflow go to a stabilization and treatment pond, which has an area of 8291.9 m^2.

Corbett #2 Farm. Corbett #2 farm (34.84 °N, 77.96 °W) is located near Rose Hill, NC, in Duplin county. Measurement campaigns were conducted during March 10–21 and June 2–13, 2003 at this farm site. A schematic layout of this potential EST including locations of flux measurements is given in Figure 6.

The ReCip encompasses two cells, or treatment basins, filled with media (proprietary technology), that would alternately drain and fill on a cyclic basis. The draining and filling cycles created aerobic, anaerobic, and anoxic conditions within the cells, providing both biotic and abiotic treatment processes to promote nitrification and denitrification. The treatment process was preceded by a solids separation step. The solid waste and the treated liquid waste went into individual lagoons, which had surface areas of 2601 m^2 and 2717 m^2, respectively. The ReCip project at the evaluation time was designed to treat only the liquid portion of the swine waste.

Vestal Farm. Vestal farm (34.93 °N, 77.94 °W) is located near Kenansville, NC, in Duplin county. NH_3 flux measurements were conducted during March 16–18, 2004, and August 4–12, 2004, respectively. A schematic layout of the EST at the Vestal Farm including the various sampling points is given in Figure 7.

The RENEW system uses a mesophilic digester as well as aeration and wastewater filtering and disinfection systems. This project also incorporated a microturbine generator. For this system, the waste first flows from the pig

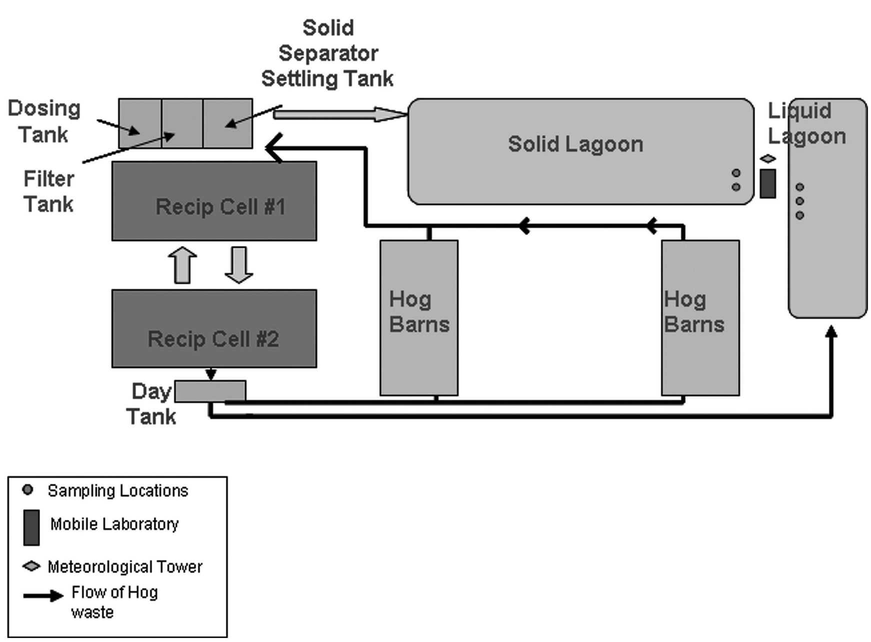

Figure 6. A schematic layout of the EST at Corbett #2 farm.

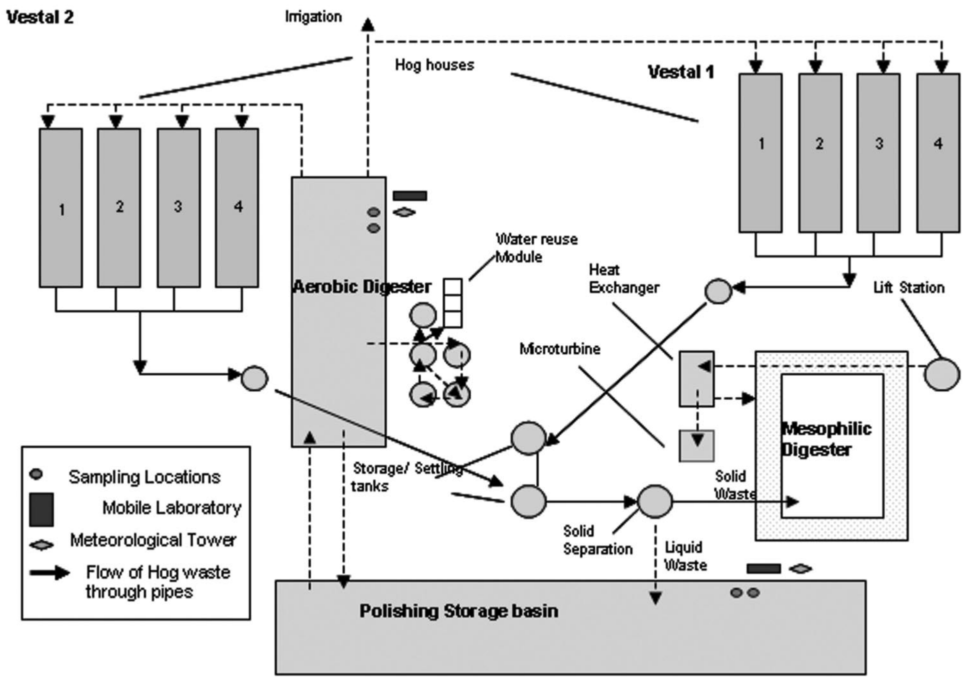

Figure 7. A schematic layout of the potential EST at Vestal farm.

barns to equalization and concentrator tanks, which serve to produce a thickened liquid. This liquid then flows to a mesophilic digester. The digester, which operates at a temperature of 95 °F, produces biogas, which is used to fuel the microturbine generator. The generator produces electricity, which is sold and used on the electric power grid. The waste stream then flows to a polishing storage basin, which has a surface area of 22,636 m^2, and then to an aerobic digester, also called a nitrification pond, which has a surface area of 1880.6 m^2. A portion of the waste stream then flows back to the polishing storage basin where it is used to flush the pig barns and is sprayed on cropland if necessary. The remaining portion of the waste stream flows through a filtration system. The filtration system consists of sand carbon filters and reverse osmosis. The water is then disinfected using ozonation and ultraviolet light. Filtered and disinfected water is then returned to the pig barns where it is used as drinking water for the pigs.

Approach to Evaluate NH_3 Emissions Reduction at EST Farms

At each EST and conventional site, the monitoring of NH_3 emissions were limited to about two 2-week periods, representing both a warm and a cool season. It was suggested that the estimated emissions from an EST for each measurement period be compared with the estimated emissions from conventional sites. However, because measurements at different sites were made at different times of the year, environmental conditions are likely to be different at different sites, even during a representative warm or cool season. Thus, there is a need for accounting for these differences in our relative comparisons of the various alternative and conventional technologies.

A rational basis for this adjustment for somewhat different environmental conditions is the development of a statistical-observational model based on multiple regression. This is developed between NH_3 emissions and measured environmental parameters at the two conventional sites.[1] Such a comparison does not require highly uncertain extrapolations of emissions at EST sites beyond the two measurement periods. It also provides a sound basis for ranking the various ESTs on the basis of their comparisons with conventional sites for each of the warm and cold seasons.

Relationships between NH_3 flux and lagoon temperature, pH, and TKN, as well as certain environmental parameters were examined in the accompanying paper, Aneja et al.[1] over a relatively wide range of lagoon temperatures (~2–35 °C) and lagoon air temperature differences that were observed during the fall and winter field campaigns at both conventional farms.

The multiple regression equation based on flux measurement data from two conventional farms is given by Aneja et al.[1]

$$\mathrm{Log}_{10}\mathrm{F} = 3.8655 + 0.04491(\mathrm{T_l}) - 0.05946(D). \quad (1)$$

Here, F denotes the average NH_3-N emission from the conventional lagoon in $\mu g \cdot min^{-1}$/1000 kg-lw (lw = live weight), where T_l is the lagoon temperature in °C, and D is a hot-air variable that is equal to zero if lagoon is warmer than air, but is equal to $\Delta T = T_a - T_l$ when $T_a > T_l$ and T_a is air temperature in °C at 10-m height. This statistical-observational model was used to estimate the projected NH_3-N flux from lagoons at the LST baseline farms to compare with the measured NH_3-N flux from water-holding structures at an EST site, for the average values of T_l and D observed at the latter.

Aneja et al.[1] describes the development of the statistical-observational model in more detail.

Table 1. The summary of animal mass, feed consumed, N content, and N excretion at EST farms.

Farm Information	Number of Pigs	Average Pig Mass (kg/pig)	Total Pig Mass (kg)	Feed Consumed (kg/pig/week)	N Content (%)	*E* (kg-N/week/1000 kg-lw)
Barham						
April 2002	4,000	238.1	952,560	12.84	2.25[a]/3.09[b]	1.65
November 2002	4,000	238.1	952,560	15.92	2.38[a]/3.43[b]	1.77
BOC #93						
April 2003	4,221	82.7	348,994	11.93	2.78	2.82
June 2003	4,373	48.0	209,952	14.41	3.24	5.25
Carrolls						
March–April 2004	6,332	59.2	374,854	12.89	2.56	3.90
June 2004	6,095	59.7	363,872	13.21	2.67	4.13
Corbett #1						
October 2003	3,386	55.4	187,584	15.44	3.01	5.86
December 2003	2,680	104.7	280,596	16.27	2.15	2.34
Corbett #2						
March 2003	1,249	98.5	123,054	16.27	2.76	3.19
June 2003	1,485	70.3	104,396	14.47	3.08	4.50
Vestal						
March 2004	9,507	38.3	364,118	10.03	2.79	5.03
August 2004	10,248	44.7	458,086	11.02	3.17	5.47

Notes: All farms are finishing operations except Barham farm, which is a farrow-to-wean operation with a mixture of sows and mature pigs. [a]N content of the feed in gestation houses; [b]N content of the feed in farrowing houses.

Estimated NH_3 emission from animal houses at a potential EST were compared with the estimated NH_3 emissions from similar houses at a conventional farm (either Moore farm—tunnel ventilated, or Stokes farm—naturally ventilated), depending on the type of the house ventilation used at the EST farm, for the same season.

Both EST emissions and conventional NH_3 emissions were normalized by the N excretion rate (E) for the farm, and are called $\%E$. On the basis of the N mass balance equation with the given animal feed information (Table 1), E in units of kg-N week^{-1} (1000 kg-lw)$^{-1}$ was determined using the following equation:

$$E = \frac{F_c \times N_f \times (1 - e_r)}{\bar{w}} \times 1000, \qquad (2)$$

where F_c is the feed consumed (kg pig^{-1} · week^{-1}), N_f is the fraction of N content in feed, e_r is the feed efficiency rate (ratio of average gain of N to N intake),[20] and $\bar{w}$ is the average live animal mass (kg/pig). The N excretion data are presented in Table 1. N excretion and NH_3-N emissions at each farm was calculated in the same units (kg-N · week^{-1} (1000 kg-lw)$^{-1}$) , thus, $\%E$ represents the loss rate of NH_3 from a source as a percentage of N-excretion rate. A potential EST was evaluated by comparison of $\%E$ value from the EST ($\%E_{EST}$) farm to $\%E$ value from a baseline conventional farm ($\%E_{CONV}$), and percent reduction of NH_3-N can be estimated as

$$\%\ reduction = \frac{(\%E_{CONV} - \%E_{EST})}{\%E_{CONV}} \times 100 \qquad (3)$$

Such percentage reductions can be estimated, separately for water-holding structures, animal houses/barns, etc., as well as for the whole EST farm. An algorithmic flow diagram for the evaluation of NH_3 emissions from water-holding structures at the EST farms is shown in Figure 8.

RESULTS AND DISCUSSION

Temporal Variations of Lagoon NH_3 Fluxes

Average NH_3 fluxes from water-holding structures at EST farms during the measurement periods are summarized in Table 2. The NH_3 flux results from all water-holding structures showed strong seasonal variation with significantly higher flux during the warm season than during the cold season at the EST farms. Seasonal differences in water-holding structure NH_3 fluxes are revealed from the composite hourly average fluxes measured at all of the EST farms, in which higher NH_3 fluxes with more clear diurnal variations were found during the warm season. Typical diurnal trends for the water-holding structure NH_3 fluxes showed low fluxes during the morning hours that increased with time during the early part of the day as the air and lagoon temperatures increased after sun rise, attaining maximum values around 3:00 p.m. and then decreasing during the evening hours. This trend was found to follow approximately the diurnal trends of air and lagoon temperatures at the experimental farms. An example of these patterns is shown in the composite hourly averaged NH_3 fluxes from the storage lagoons at Barham and Corbett #2 farms (Figure 9, a and b).

NH_3 Emissions from Water-Holding Structures

Average fluxes and total estimated emissions from water-holding structures are presented in Table 2. Flux measurements of NH_3 at the Barham farm were conducted from storage and overflow lagoons at the farm. For the April 2002 measurement campaign, the EST at the farm was not fully functioning and did not achieve steady state. The fluxes from the water-holding structures were found to be

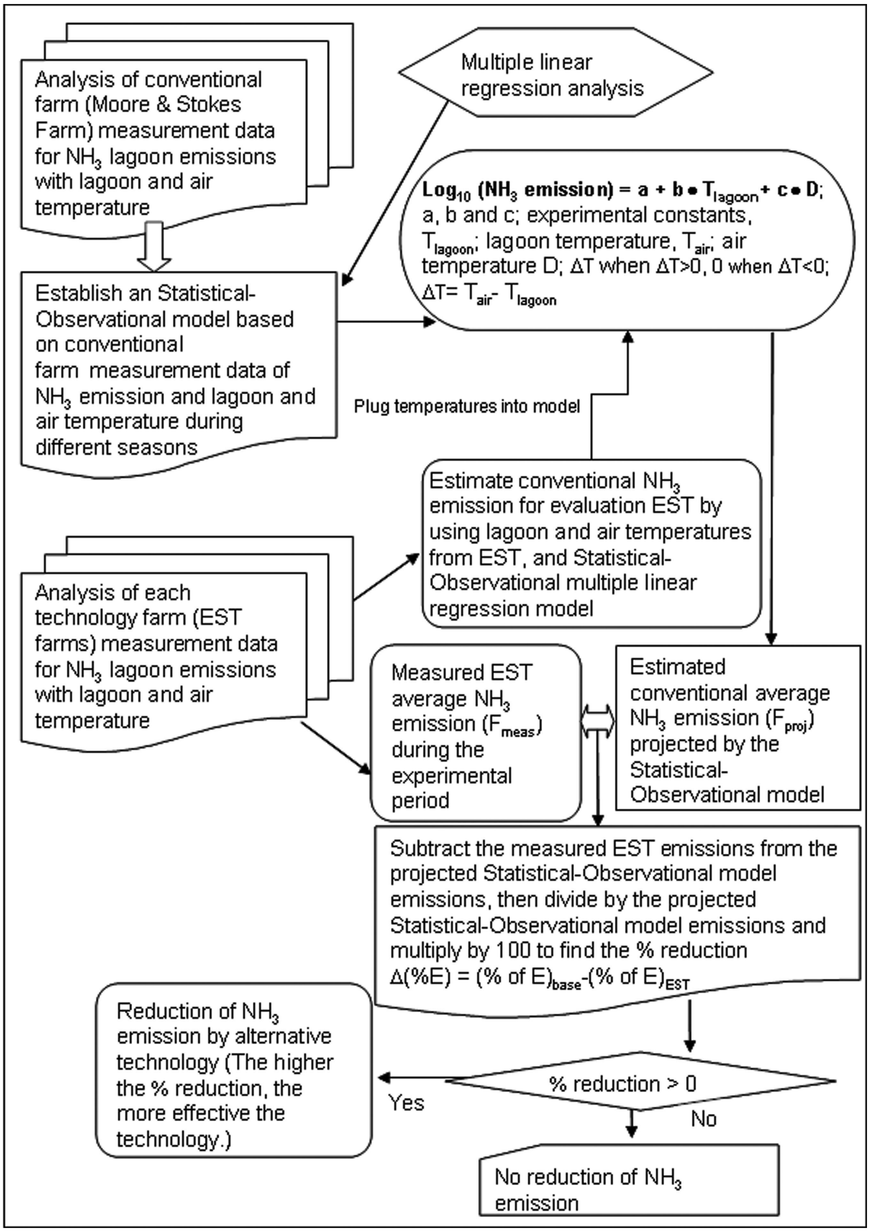

Figure 8. Algorithm flow chart for evaluation of EST NH_3 emissions from water-holding structures.

higher in the warm season than in the cold season. In the warm season, the overflow lagoon had a slightly higher flux, whereas in the cool season the storage lagoon had a higher flux. Overall, the weekly emissions were three to five times higher in the overflow lagoon than in the storage lagoon. This is a result of the overflow lagoon's area being approximately five times larger.

At BOC #93 farm, fluxes were measured from three water-holding structures: (1) the treated effluent lagoon, (2) the biosolids lagoon, and (3) and the equalization tank. In the warm season, the fluxes were higher for both the treated effluent lagoon and the biosolids lagoon than in the cool season, but the flux was lower in the warm season for the equalization tank. This is because the tank has a controlled temperature. For the cool season evaluation, the average fluxes from the three water-holding structures are very similar, with the treated effluent lagoon having the highest flux. Overall the emissions were highest from the biosolids lagoon, which had the largest surface area. The equalization tank had the smallest (negligible) emissions of the water-holding structures because of its small surface area.

At Carrolls farm, NH_3 fluxes were measured from the ABS lagoon, and from the east and west sides of the aeration lagoon. For both the warm season and the cool season, the ABS lagoon had the highest flux. Flux was higher in the warm season than the cool season for the ABS lagoon. A different pattern was observed for the aeration lagoon, where the fluxes were unusually higher in the cool season. Emissions followed the same pattern as fluxes, with the ABS having significantly larger emissions than the aeration lagoon.

Corbett #1 contained two water-holding structures: a stabilization lagoon and a feed tank. For the warm season evaluation, the flux was four times higher in the feed tank than in the stabilization lagoon; however, emissions were

Table 2. Estimated NH_3 emissions from water-holding structures at six EST farms during the experimental periods.

Farm Name and Sampling Period	Water-Holding Structure	Average 15-min Flux ($\mu g\ NH_3\text{-}N\ m^{-2}\ min^{-1}$)	Water-Holding Structure Surface Area (m^2)	Weekly NH_3 Emissions (kg-N/week)	Total Emissions from Water-Holding Structures (kg-N/week)	Total Emission/Pig (kg-N/pig/week)	Total Emission/1000 kg-lw (kg-N/1000 kg-lw/week)
Barham April 2002	Storage lagoon	1101.9 ± 64.2	4,459	49.53	293.08	0.073	0.31
	Overflow lagoon	1245.6 ± 175.1	19,398	243.55			
Barham November 2002	Storage lagoon	435.8 ± 39.2	4,459	19.59	65.36	0.016	0.07
	Overflow lagoon	234.1 ± 34.0	19,398	45.77			
BOC #93 April 2003	Treated effluent lagoon	1711.0 ± 329.6	1614.6	27.92	79.21	0.019	0.23
	Biosolids lagoon	1556.5 ± 430.1	3229.2	50.81			
	Equalization tank	1673.4 ± 515.8	28.3	0.48			
BOC #93 June 2003	Treated effluent lagoon	2473.3 ± 928.8	1614.6	40.36	122.1	0.028	0.58
	Biosolids lagoon	2491.5 ± 537.1	3229.2	81.32			
	Equalization tank	1474.5 ± 643.6	28.3	0.42			
Carrolls March–April 2004	East side of aeration lagoon	480.2 ± 93.0	3304.8	14.9	80.4	0.013	0.21
	West side of aeration lagoon	446.7 ± 123.1	6010.2	29.1			
	ABS lagoon	713.1 ± 106.3	5068.8	36.4			
Carrolls June–July 2004	East side of aeration lagoon	209.4 ± 14.4	3304.8	4.2	83.1	0.014	0.23
	West side of aeration lagoon	127.5 ± 32.9	6010.2	12.7			
	ABS lagoon	1295.8 ± 135.6	5068.8	66.2			
Corbett #1 October 2003	Stabilization lagoon	734.0 ± 246.7	8291.8	61.51	62.33	0.018	0.33
	Feed tank	2992.6 ± 109.0	27.1	0.82			
Corbett #1 December 2003	Stabilization lagoon	415.2 ± 84.2	8291.8	34.8	34.8	0.013	0.12
Corbett #2 March 2003	Solid storage lagoon	472.6 ± 174.6	2601	12.39	42.51	0.034	0.35
	Liquid storage lagoon	1100.5 ± 457.6	2717	30.12			
Corbett #2 June 2003	Solid storage lagoon/	1624.3 ± 558.9	2601	42.59	84.36	0.057	0.81
	liquid storage lagoon	1525.2 ± 469.2	2717	41.77			
Vestal March 2004	Aerobic digester	1010.7 ± 60.7	1880.6	19.2	149.9	0.016	0.39
	polishing storage basin	573.1 ± 136.7	22,636.0	130.8			
Vestal August 2004	Aerobic digester	840.6 ± 284.8	1880.6	15.9	490.7	0.048	1.07
	polishing storage basin	2080.7 ± 340.8	22,636.0	474.8			

two orders of magnitude higher from the stabilization lagoon. This is likely due to the stabilization lagoon having a significantly larger surface area. For the December measurement period, measurements were only made at the stabilization lagoon. This was because of the malfunction of the dynamic flow-through chamber used for the feed tanks. This is not thought to be a problem because of the relatively small emissions observed in the October evaluation period. For the stabilization lagoon, the flux was lower in the cool season than in the warm season.

NH_3 fluxes at Corbett #2 farm were measured from the solid storage and the liquid storage lagoons. Emissions for both of these water-holding structures were lower in the cool season than the warm season. In the cool season, the liquid storage lagoon had the higher flux. Conversely, in the warm season, the solid storage lagoon had the higher flux. Both water-holding structures have similar surface areas, and therefore the same pattern was repeated for the emissions.

Vestal farm contained two water-holding structures, an aerobic digester, and a polishing storage basin. For the polishing storage basin, the flux was higher in the warm season than the cool season. This pattern was not observed for the aerobic digester, where the emissions in the digester were slightly lower in the warm season than in the cool season. The larger area of the polishing storage basin resulted in much higher emissions for both the cool and warm periods.

Total emissions (kg-N/1000 kg-lw/week), normalized by live animal mass at the farm, were calculated for each experimental period for each EST farm (see Table 2). The emissions for the cool season for all EST farms ranged from 0.07 to 0.39 kg-N/1000 kg-lw/week, with a mean value of 0.23 kg-N/1000 kg-lw/week. The emissions for

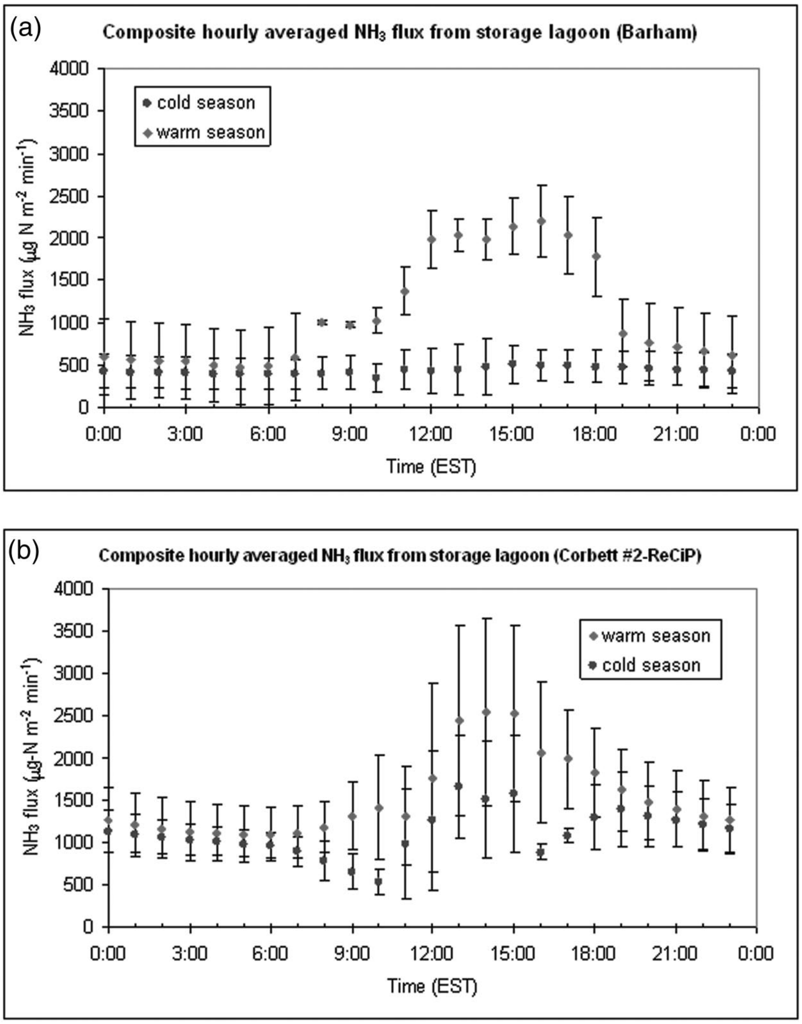

Figure 9. (a) Composite hourly averaged NH_3 flux from storage lagoon during April (warm season) and November (cold season), 2002 measurement periods at Barham farm. Error bar indicates ±1 standard deviation. (b) Composite hourly averaged NH_3 flux from storage lagoon during March (cold season) 2002 and June (warm season) 2003 measurement periods at Corbett #2 farm. Error bar indicates ±1 standard deviation.

the warm season for all EST farms ranged from 0.31 to 1.07 kg-N/1000 kg-lw/week, with an average value of 0.56 kg-N/1000 kg-lw/week. For all six EST farms, the total emissions were much higher in the warm season than the cold season, with the exception of the Carrolls farm where the seasonal difference was small.

NH_3 Emissions from Housing Units (Barns)

Table 3 shows the overall averages for the NH_3 emissions estimated by OP-FTIR measurements made during the sampling periods from the swine barns at the six EST farms. Emissions for the cool season for all of the EST farms ranged from 0.008 to 0.98 kg-N/1000 kg-lw/week, with an average value of 0.37 kg-N/1000 kg-lw/week. For the warm season, emissions ranged from 0.16 to 1.29 kg-N/1000 kg-lw/week, with a mean value of 0.70 kg-N/1000 kg-lw/week. Higher emissions from the barns were experienced during the warm period at five of six EST farms; the exception was the Barham farm. Emissions from naturally ventilated barns were noticeably lower on days when the curtains were closed to block the wind and maintain heat in the barn.

Evaluation of Total NH_3 Emissions from EST Farms

To calculate the total percent reduction, the sum of projected emissions and measured emissions were taken for

Table 3. Estimated NH_3 emission from the swine houses at EST farms during the experimental periods (OP-FTIR measurements).

EST Farms	Sampling Periods	Barn Emissions (kg-N/1000 kg-lw/week)
Barham	April 2002	0.34
	November 2002	0.49
BOC # 93	April 2003	0.57
	June 2003	1.29
Carrolls	March–April 2004	0.98
	June–July 2004	1.15
Corbett # 1	October 2003	0.16
	December 2003	0.008
Corbett # 2	March 2003	0.12
	June 2003	0.52
Vestal	March 2004	0.07
	August 2004	0.75

Table 4. Summary of NH_3 emissions from the EST farms and percent reduction during the experimental periods.

EST Farms	Sampling Periods	Emission Sources	Measured Emission (F_{meas}; kg-N/week/1000 kg-lw)	$\%E_{EST}$	$\%E_{EST}$ (WHS + House)	EST Average Lagoon Temperature (°C)	EST Average *D* (°C)	Conventional Lagoon Emission (model/estimated; kg-N/week/ 1000 kg-lw(F_{proj})	$\%E_{CONV}$	$\%E_{CONV}$ (Lagoon + House)	Percent Reduction
Barham	April 2002	WHS	0.31	18.8	39.4	17.2	0.7	0.4	11.3	35.2	−11.9
		House	0.34	20.6				1.05	23.9[a]		
	November 2002	WHS	0.07	4.0	31.7	14.2	0.3	0.31	9.7	32.5	2.5
		House	0.49	27.7				0.89	22.8[b]		
BOC #93	April 2003	WHS	0.23	8.2	28.4	18.5	0.7	0.46	14.3	37.1	23.5
		House	0.57	20.2				0.89	22.8 [b]		
	June 2003	WHS	0.58	11.0	35.6	28.6	0.3	1.38	38.9	62.8	43.3
		House	1.29	24.6				1.05	23.9		
Carrolls farm	March–April 2004	WHS	0.21	5.4	30.5	15.0	0.0	0.34	10.6	33.4	8.7
		House	0.98	25.1				0.89	22.8[b]		
	June–July 2004	WHS	0.23	5.6	33.4	29.1	0.0	1.50	42.2	66.1	49.5
		House	1.15	27.8				1.05	23.9		
Corbett #1 farm	October 2003	WHS	0.33	5.6	8.3	21.8	0.2	0.69	19.4	29.4	71.8
		House	0.16	2.7				0.25	10.0[c]		
	December 2003	WHS	0.12	5.1	5.4	9.3	0	0.19	5.9	15.9	66.0
		House	0.008	0.3				0.25	10.0[c]		
Corbett #2 farm	September 2003	WHS	0.35	11.0	14.8	14.9	1.6	0.28	8.7	18.7	20.9
		House	0.12	3.8				0.25	10.0[c]		
	December 2003	WHS	0.81	18.0	28.9	24.1	1.0	0.78	22.0	32.0	9.7
		House	0.49	10.9				0.25	10.0[c]		
Vestal	March 2004	WHS	0.39	7.8	9.2	14.8	0.6	0.32	10.0	20.0	54.0
		House	0.07	1.4				0.25	10.0[c]		
	August 2004	WHS	1.07	19.6	33.3	28.5	0.3	1.36	38.3	48.3	31.1
		House	0.75	13.7				0.25	10.0[c]		

Notes: [a]NH_3 emission measured from barns at tunnel (fan) ventilated conventional farm (Moore farm) during October 2002; [b]NH_3 emission measured from barns at tunnel (fan) ventilated conventional farm (Moore farm) during February 2003; [c]NH_3 emission measured from barns at naturally ventilated conventional farm (Stokes farm) during January 2003. WHS = water-holding structures.

the water-holding structures and barns. These numbers were then used to calculate total percent reduction using the same process that was applied individually for water-holding structures and barns.

Table 4 shows the summary of the total NH_3 emissions measured from all six EST farms, along with the projected emissions from the LST farms and the percent reduction values for their evaluation of potential N reduction.

Out of six EST farms, five show percent reduction in NH_3 emissions for both experimental periods. The BEST technology used at Corbett #1 was the most successful, with a reduction of 71.8% in the warm season, and 66% in the cool season. The next largest percent reduction was the ISSUES-RENEW system used at Vestal farm, with percent reductions of 54 and 31.1% for cool and warm seasons, respectively. The next most effective was the EKO-KAN technology at BOC #93 farm, which had percent reductions of 23.5 and 43.3% for the cool and warm seasons, respectively. A further technology with reduction in both seasons was the ISSUES-PBS, which was located at Carrolls farm. There was a small reduction of 8.7% in the cool season, and a larger reduction of 49.5% in the warm season. The ReCip technology was only slightly effective, with small reductions in both seasons of 20.9 and 9.7%, respectively.

The technology at Barham farm was less effective with mixed results, reducing emissions slightly in one experimental period, but enhancing in the other. This could be the result of the EST at Barham farm not being fully functional. The technology did not achieve steady state until the April 2002 sampling period. However, this does not explain the insignificant percent reduction during the November 2002 experimental period.

CONCLUSIONS

A rational and functional approach to study NH_3 emissions at commercial-scale animal production agricultural farms was developed.

Six potential ESTs were evaluated to determine if they would substantially reduce atmospheric emissions of NH_3 at swine facilities from their estimated or projected emissions in comparison to what had been observed on two conventional LST swine farms during two different (warm and cold) experimental periods. Five of six farms showed varying amounts of percent reductions in NH_3 emissions for both experimental periods.

One of the five ESTs showed an appreciable percent reduction in NH_3 emissions for both periods. The technology used at Corbett #1 had the highest percent reductions of 71.8 and 66% for the warm and cool seasons, respectively.

However, on the basis of our evaluation results, analysis, and available information in the scientific literature, the evaluated alternative technologies may require additional technical modifications to be qualified as unconditional ESTs relative to NH_3 emissions reductions.

This study did not address the potential reductions in odor and pathogens by the potential ESTs. Other scientists in the OPEN project evaluated those environmental factors.

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