

## ABSTRACT

BALLA, BISWA KUMAR. Determining Plant-Available Nitrogen in Hog Anaerobic Lagoon Effluent Applied with Traveling Gun and Drag Hose Systems. (Under the direction of Sanjay Bikram Shah.)

Currently, the plant-available nitrogen (PAN) coefficient of hog anaerobic lagoon effluent does not differentiate for land application by broadcast (e.g. drag hose) or irrigation (e.g. traveling gun). There is a need to determine PAN coefficients for traveling gun and drag hose by measuring ammonia ( $\text{NH}_3$ ) emissions, and accounting for partial nitrogen (N) mineralization. Ammonia emissions were measured for four application periods (fall, spring, 2 summer) with the integrated horizontal flux (IHF) method on Bermudagrass grown on Cainhoy sand in Garland, NC. Ammonia concentration was measured using acid scrubbers. Nitrogen mineralization was estimated based on published literature. During application by traveling gun 3 to 9% of applied-N was lost as  $\text{NH}_3$  before it hit the ground (soil or canopy surface). Total  $\text{NH}_3$  emission from the ground ranged from 13 to 26% of applied-N, 96 h after start of the application. The first 4 h accounted for 65 to 81% of the  $\text{NH}_3$  emission. The N loss during application (in the trajectory) ranged from 4 to 11%. Due to uncertainties in the  $\text{NH}_3$  emission measurement, additional studies are needed with improved methods to account for losses in the trajectory and subsequent mist formation during application. Ammonia-N emission using the drag hose, ranged from 1 to 5%. Based on literature, the organic-N mineralization rate was assumed to be 50%. The PAN, thus obtained, was 0.65 for traveling gun, and 0.85 for drag hose. A model was used to simulate  $\text{NH}_3$  emission from hog lagoon effluent applied with both the traveling gun and drag hose. The model underestimated  $\text{NH}_3$  emission from traveling gun treated plot for all four periods. The model overestimated

emissions from drag hose treated plot in two of the three periods. The model was sensitive to increase in soil pH and moderately sensitive to changes in all other selected parameters (total ammoniacal-N concentration and pH of effluent, linear partition coefficient of soil, and wind speed).

Determining Plant-Available Nitrogen in Hog Anaerobic Lagoon Effluent  
Applied with Traveling Gun and Drag Hose Systems

by  
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## **BIOGRAPHY**

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# 1. INTRODUCTION

## 1.1. Background

North Carolina (NC) produces 9.6 million hogs per year, making it the second largest hog producing state in the U.S., behind Iowa (Aneja et al., 2000). Hog waste in NC is mostly treated in anaerobic lagoons. The anaerobic lagoon effluent is periodically applied to crop or pasture land as a nutrient source for plants. Anaerobic hog lagoon effluent contains on average 600 mg/L of nitrogen (N), 340 mg/L of phosphorus (P) and 800 mg/L of potassium (K), expressed as N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O, respectively (Barker et al., 1994). Land application of hog lagoon effluent is based on a nutrient management plan, to ensure that N is not over-applied. The over application of nutrients could result in some of the nutrients finding pathways to surface or ground waters, and thus polluting them. Application of hog waste also results in emissions of ammonia (NH<sub>3</sub>), an air pollutant. Apart from the loss of N into the environment, only a portion of organic-N (org-N) in the effluent may mineralize and be available for crop growth. These N losses, or their reduced availability, if not taken into account, may result in under-application of N. Less than optimal N may result in reduced crop yield. Hence, plant-available nitrogen (PAN) coefficients have been used by regulatory agencies (e.g., NC Division of Water Quality Animal Feeding Operations) to ensure optimal N application and minimize N losses into the environment.

Hog lagoon effluent can be irrigated, broadcasted on the land surface, broadcasted and incorporated, or injected below the surface. A tanker with splash plate or drop hose is broadcast system; traveling gun and center pivot irrigation are examples of irrigation.

A traveling gun consists of a wheeled cart with a large sprinkler (more commonly called “gun,” “big gun” or “traveling gun”), the main traveler with a hose reel, and an irrigation hose. The wheeled cart is pulled either by a cable or a hard irrigation hose during operation. The “gun” travels while irrigating; hence, the term traveling gun. One of the major benefits of the traveling gun system is that it can be moved quite easily. Its major drawback is it cannot be used on irregularly shaped fields. The traveling gun sprays a stream of water (or wastewater) high in the air during irrigation, which increases drift. Even with the drawbacks mentioned, the flexibility and portability of the traveling gun make it the only real solution in some instances (Barker et al., 1994).

A drag hose system uses a hose to convey lagoon effluent from a lagoon to a tractor-drawn application unit. The unit has a distribution box and an attachment that allows the effluent to be broadcasted and/or partially incorporated into the soil. The drag hose system is gaining popularity in NC because it has higher application rates (vs. other methods), reducing time and energy use. The system can be used to apply closer to boundaries in irregular shaped fields. The effluent is applied at low pressure and close to the ground, which reduces drift and odor problems. However some drawbacks of the drag hose system include high initial cost, requirement of tractor and tractor operator (Barker et al., 1994).

The land applied N is taken up by plants to synthesize protein. Animals get protein by consuming plants as feed for growth and metabolism. The unutilized protein in animal diet is excreted as N in the form of urea (in urine) and organic-N (in feces). Urea is quickly transformed into ammonium-N ( $\text{NH}_4^+\text{-N}$ ); some of the  $\text{NH}_4^+$  may be transformed into  $\text{NH}_3$  and lost through emission (volatilization).

Ammonia emission from animal feeding operations is a concern in the U.S. (EPA, 2001). A portion of emitted  $\text{NH}_3$  is deposited in the vicinity through dry deposition while the remainder may transform into  $\text{NH}_4^+$  aerosols. The aerosols can travel long distance before they are deposited by rainfall (wet deposition). Nitrogen deposition and formation of aerosols are cited as the main problems of  $\text{NH}_3$  emissions (Arogo et al., 2003). Although many nutrient deficient parts of the world benefit from N deposition, some areas, particularly the coastal areas of U.S., are adversely affected by harmful algal blooms (eutrophication) (Rabalais et al., 2002).

The role of N in aquatic ecosystems has received considerable scrutiny due to its contribution to eutrophication. Algal blooms result in low dissolved oxygen (hypoxic) regions. Hypoxia inhibits aquatic life and reduces fishery production. In addition, some algal blooms may produce toxins that result in fish lesions and fish kills (Rabalais et al., 2002). In terrestrial ecosystems, under aerobic conditions, total ammoniacal-N (TAN) can be transformed into nitrate-N ( $\text{NO}_3^-$ -N), which is soluble in water. The  $\text{NO}_3^-$ -N can leach through the soil into groundwater. Nitrate-N is harmful if it gets into public water supply. The digestive tract of a baby can convert the nitrate to nitrite. Nitrite contributes to an oxygen deficient condition called methemoglobinemia or “blue baby syndrome”, which can be fatal (Addiscott and Benjamin, 2004). Newborn babies are particularly susceptible to methemoglobinemia. Hence the, U.S. EPA has set a maximum contaminant level (MCL) of 10 parts per million (ppm) for  $\text{NO}_3^-$ -N in public water supply (EPA, 2000).

It is clear from the preceding discussion that the method of effluent application may impact the amount of N loss into the environment. Hence, the application method may

impact PAN. However in NC, a single PAN coefficient of 0.50 is used for both the traveling gun and the drag hose systems. Hence, there may be a need to develop separate PAN coefficients for the traveling gun and drag hose systems.

## **1.2. Objectives**

The overall objective of this study was to determine the PAN coefficients of hog anaerobic lagoon effluent land applied by two methods, namely, traveling gun and drag hose.

The specific objectives were to:

1. Compare  $\text{NH}_3$  emissions from the two systems.
2. Estimate the PAN in anaerobic hog lagoon effluent applied using the two methods based on measured  $\text{NH}_3$  emissions and estimated org-N mineralization rates.
3. Test the mathematical model developed by Wu et. al. (2003) for its ability to simulate emissions from hog lagoon effluent applied using the traveling gun and drag hose.

## 2. LITERATURE REVIEW

In this chapter, various techniques used to measure  $\text{NH}_3$  are presented. Methods of using the  $\text{NH}_3$  concentration to quantify  $\text{NH}_3$  emission are discussed. Previous studies on  $\text{NH}_3$  emissions from land applied effluent are summarized. Loss of N from effluent due to partial N mineralization rates following land application is discussed. Finally,  $\text{NH}_3$  volatilization modeling is discussed.

### 2.1. Quantification of Ammonia Emission

To quantify  $\text{NH}_3$  emission (vertical flux or volatilization),  $\text{NH}_3$  concentration in the air and the air flowrate or airspeed over the treated surface are measured. Details on methods used to measure  $\text{NH}_3$  concentration and  $\text{NH}_3$  emissions are discussed below.

#### 2.1.1. Ammonia concentration measurement

Acid scrubbers, filter packs, denuders, and optical methods are used to measure concentration of  $\text{NH}_3$  in air (Shah et. al., 2006). These methods are briefly discussed below.

##### 1. Acid Scrubber

In an acid scrubber,  $\text{NH}_3$  is converted to an  $\text{NH}_4^+$  salt when air containing  $\text{NH}_3$  is passed thorough an acid solution. The  $\text{NH}_4^+$  concentration in the scrubber solution is analyzed in the laboratory using ion chromatography, selective electrode, colorimetry, or titrimetry. Chantigny et al. (2004) used a scrubber with 0.005 M phosphoric acid ( $\text{H}_3\text{PO}_4$ ) for capturing

NH<sub>3</sub>. Huijismans et al. (2003) used acid scrubbers in a study that compared NH<sub>3</sub> emissions from different land application methods. The advantages of scrubbers include high trapping efficiency (>97%) (over wide range of NH<sub>3</sub> concentrations, acid strengths, air flow rates, durations, and diffuser types) and moderate cost. The disadvantages include power requirement, inability to separate NH<sub>4</sub><sup>+</sup> and NH<sub>3</sub>, and loss of volume of acid over time resulting in decreased scrubber efficiency when deployed over long durations (Shah et al., 2006).

## 2. Filter Pack

A filter pack consists of a structure containing an acid-coated filter paper. In forced air filter packs, convective flow transports NH<sub>3</sub> to the filter; in passive filter packs, diffusion is the predominant mode of NH<sub>3</sub> transport. After a certain duration of sampling, the filter is extracted with distilled water and the solution is analyzed for NH<sub>4</sub><sup>+</sup> in the lab. In passive filter packs, NH<sub>3</sub> concentration is calculated by correlating NH<sub>3</sub> recovery with concentrations measured with scrubbers or calibrated in wind tunnels with known NH<sub>3</sub> concentrations. Filter packs have detection limits of 0.2 to 2.8 µg/filter depending upon design, preparation and analytical methods. Filter packs have low cost, and are easy to operate. However, the disadvantages include short deployment time, and requirement of quality control during preparation, handling, and analysis (Shah et al., 2006).

### 3. Denuders

A denuder consists of a tube coated or packed with an acidic or sorbent medium. Ammonia diffuses into the medium and forms  $\text{NH}_4^+$  salt when air passes through the tube. Various types of denuders have been used: simple denuders, annular denuders, acid coated denuders, and honey-comb type denuders. The simple denuder (coated with acid) used by Ferm (1979) had an  $\text{NH}_3$  trapping efficiency of 95.6-99.8%. The honey-comb type denuder had an  $\text{NH}_3$  trapping efficiency of 70.1 to 99.6% and the annular denuder's efficiency was 54.6 to 99.6% (Possanzini et al., 1983). Svensson (1994) used a passive denuder to measure  $\text{NH}_3$  concentration. Passive denuders can be used to estimate emissions without measuring wind speed, and they cost less than forced air denuders. Passive denuders are preferable when real-time flux data are not required (Shah et al., 2006).

### 4. Optical methods

Optical methods include chemiluminescence, spectroscopy, and fluorescence. In chemiluminescence,  $\text{NH}_3$  is converted to nitric oxide (NO), which is measured. In spectroscopy, change in spectrum due to absorption of radiation at specific wavelengths allows determination of  $\text{NH}_3$  concentration. In fluorescence,  $\text{NH}_3$  is photo-fragmented thrice using the vacuum UV PF/LIF (Ultra-violet Photofragmentation-Laser Induced Fluorescence) method, and the fluorescence of its final photo-fragment is measured to calculate concentration of  $\text{NH}_3$  (Schendel et al., 1990). Rumburd et al. (2006) measured atmospheric  $\text{NH}_3$  using an open path differential optical absorption spectroscopy (DOAS) method. Optical methods can be used to measure real-time data at very low concentrations. The disadvantages

of optical methods are expensive equipment, and high logistic support requirements making long-term deployment in the field difficult (Shah et al., 2006).

### **2.1.2. Ammonia emission measurement**

Ammonia emissions are measured using enclosures, N recovery (N balance), and micrometeorological methods. The N recovery is used as an indicator of relative  $\text{NH}_3$  loss, as N can be lost in other gaseous forms as well (Shah et al., 2006); hence, it is not recommended for measuring emissions or even for comparing  $\text{NH}_3$  emissions. Selection of a particular method depends on the project objective, size of the plot, cost, time and labor available (Shah et al., 2006). The enclosure and micrometeorological methods are discussed below.

#### **1. Enclosure method**

The enclosures can be closed-static (completely sealed), semi-open (airflow only through diffusion and natural convection), or dynamic chambers (airflow using fan or pressurized air) (Marshall and Debell, 1980). Ammonia emission is determined based on  $\text{NH}_4^+$  recovered on a trapping medium and the chamber area. In dynamic chambers, which include wind tunnels, airflow rate through the chamber is measured. Enclosures can be used to compare relative emissions when the  $\text{NH}_3$  sources are applied uniformly. Since they modify the environment, they are not suitable for measuring emissions. Wind tunnels are more suitable than chambers for testing  $\text{NH}_3$  volatilization models (Shah et al., 2006).

## 2. Micrometeorological methods

Four micrometeorological methods: integrated horizontal flux (IHF), gradient diffusion, eddy correlation, and backward Lagrangian stochastic (bLS) model are presented. A major advantage of the micrometeorological methods (vs. enclosures) is that they do not modify the environment. More detailed description is given in Shah et al. (2006).

A. Integrated horizontal flux (IHF) or mass balance method: In the IHF method,  $\text{NH}_3$  emissions from a treated surface transported horizontally by wind, is captured in a vertical plane downwind of the source. The vertical  $\text{NH}_3$  flux is calculated using eq. [2.1].

$$\Phi = \frac{1}{x} \left[ \int_{z_0}^{z_p} (\overline{uC_g})_e dz - \int_{z_0}^{z_p} (\overline{uC_g})_b dz \right] \quad [2.1]$$

where,  $\Phi$  = ammonia flux,  $\text{mg m}^{-2} \text{s}^{-1}$

$x$  = fetch, m

$u$  = average horizontal wind speed at a height  $z$ , averaged over a sampling period, m/s

$C_g$  = average concentration of  $\text{NH}_3$  at the height  $z$  over the sampling period,  $\text{mg/m}^3$

$z_0, z_p$  = limiting heights over which  $u$  and  $C_g$  are integrated ( $z_0$  is the roughness parameter and  $z_p$  is the height of profile development)

$z_0$  is a function of canopy height,  $h$ , and is calculated as:

$$\log_{10} z_0 = 0.997 \log_{10} h - 0.883 \quad [2.2]$$

The subscripts e and b in Eq. [2.1] denote parameters ( $u$  and  $C_g$  in this case) associated with the treated plot and background, respectively. The background flux is deducted to obtain net emission from the treated surface. In the IHF method, measurements of  $\text{NH}_3$  concentrations and wind speeds have to be made at multiple heights. The ZINST method-Is a subset of the IHF method. The method requires measurement of  $u$  and  $C_g$  at only a single height to determine  $\text{NH}_3$  emission. The height is a function of  $z_0$  (where  $z_0$  is a function of aerodynamic roughness) and plot radius. It requires a well-developed normalized flux profile to minimize error. The advantage of the IHF method-Is its simple yet robust theoretical basis with very few assumptions. The IHF method allows the use of passive flux samplers, in which  $\overline{uC_g}$  can be calculated without measuring  $u$  and  $C_g$  separately (Shah et al., 2006).

B. Gradient diffusion: The  $\text{NH}_3$  emission is determined by calculating eddy diffusivity and the concentration gradient at two heights. The aerodynamic and energy balance methods are two methods based on gradient diffusion. The application of the gradient diffusion method requires a plot with a large fetch, where the vertical  $\text{NH}_3$  concentration profile is in equilibrium with local rate of exchange and horizontal concentration gradient is negligible (Shah et al., 2006).

C. Eddy correlation: The mean vertical wind speed is assumed to be zero over a flat, uniform surface; hence  $\text{NH}_3$  emissions are equal to fluctuations of vertical wind speed and  $\text{NH}_3$  concentrations. The method requires rapid measurements of vertical wind speed and concurrently occurring gas concentrations. A modification of this method, relaxed eddy

accumulation does not require instantaneous gas concentration measurements (Shah et al., 2006).

D. Backward Lagrangian stochastic (bLS): The bLS model is based on a 3-D model for Gaussian turbulence used with a standard Monin-Obukhov formula (Flesh et al., 2002). The model is run from a tower downwind of the gas source. Wind speed, wind direction, and  $\text{NH}_3$  concentration are measured at the tower. For this method, scrubber or denuders are not required. However the model does not perform well under stable conditions and transition periods (Shah et al., 2005). Due to their low cost, acid scrubbers is suitable for time-averaged  $\text{NH}_3$  concentration measurement in field for multiple days. For the determination of  $\text{NH}_3$  emission in those conditions, the IHF method is preferred because of its simple yet sound theoretical basis and ability to provide area and time-averaged  $\text{NH}_3$  emissions. Moreover, unlike the other micrometeorological methods, the IHF method can be applied to small plots (Shah et al., 2006).

## **2.2. Past Studies on Ammonia Emissions**

Many studies have been conducted to measure  $\text{NH}_3$  emissions from land applied lagoon effluent. Selected studies are discussed below.

Montes and Chastain (2003) measured  $\text{NH}_3$  losses following irrigation of hog effluent (12 events) in a commercial pine plantation in South Carolina. Effluent was incorporated immediately after application. Ammonia emissions were measured using three wind tunnels.

Ammonia concentrations were measured using gas detector tubes. The  $\text{NH}_3\text{-N}$  lost ranged from 0 to 4% of applied TAN (Montes and Chastain, 2003).

Sullivan et al. (2003) measured  $\text{NH}_3$  emission after land application of hog lagoon effluent on 0.115 ha circular bermudagrass plot by sprinkler irrigation in Alabama. Ammonia emission was measured using the IHF method;  $\text{NH}_3$  concentrations were measured on a 3-m high mast fitted with passive denuders at different heights. Masts were placed at the center of each plot, and a mast was also placed upwind of the plot to determine background  $\text{NH}_3$  concentration. Ammonia-N emissions ranged from 8 to 30% of applied N (Sullivan et al., 2003).

Sharpe and Harper (2002) measured  $\text{NH}_3$  emission from land applied anaerobic hog lagoon effluent on soybean field in the Coastal Plains of North Carolina. The emissions were monitored for 5 d. They measured wind speed and air temperature at six heights (canopy height plus 0.2, 0.4, 0.6, 0.8, 1.6, and 2.7 m). Concentrations of  $\text{NH}_3$  in air were measured using tunable diode laser (TDL) spectroscopy. Ammonia emissions were then determined using the gradient diffusion method. After three irrigation events, ~35% of the effluent N applied was volatilized (Sharpe and Harper, 2002).

Al-Kaisi and Waskom (2002) estimated  $\text{NH}_3$  loss from swine lagoon effluent after sprinkler irrigation, during 1997 to 1999 in Colorado, in fallow corn plots. One site had a two-stage anaerobic lagoon and the other two sites had one-stage lagoons. The mass balance approach, TAN concentration difference between lagoon and catch cans, was used to calculate  $\text{NH}_3$  loss from sprinkler system and before and after application soil  $\text{NH}_4\text{-N}$  content to estimate  $\text{NH}_3$  loss from soil. Total  $\text{NH}_3\text{-N}$  losses ranged from 63 – 73% of applied-N when

the air temperature ranged from 7.2 – 18.9° C and 33 – 42% when the air temperature was minus 2.6°C (Al-Kaisi and Waskom, 2002).

Safley et al. (1992) determined the NH<sub>3</sub> loss during land application of hog lagoon liquid on bare soil using center pivot irrigation system. Ammonia losses from the center pivot ranged from 14 to 37% of applied-N; of this loss, 62-100% was due to evaporation and drift.

The reported NH<sub>3</sub>-N emissions, following land application of hog lagoon effluent, ranged from 8 to 73% of applied-N. The high variation might be partly due to different NH<sub>3</sub> concentrations and emissions methods used as well as dependence of emissions on various soil, environmental, effluent, and application equipment factors.

### **2.3. Nitrogen Mineralization**

Anaerobic lagoon effluent contains N in the forms of TAN, NO<sub>3</sub>-N and org-N. Average org-N as percentage of total N in swine lagoon effluent is ~20% (Barker et al., 1994). Organic-N has to be mineralized into inorganic forms for it to become available for crop uptake. Mineralization is carried out by micro-organisms and extracellular enzymes such as protease, deaminase, and urease (Zaman et al., 1999).

There are few studies on N mineralization following land application of hog lagoon effluent. However, there are many studies on N mineralization following application of anhydrous NH<sub>3</sub>, municipal waste effluent, animal manure, and dairy lagoon effluent. Selected studies are discussed below.

Habteselassie et al. (2006) incorporated liquid dairy waste into the top 150 mm of calcareous Millville silt loam soil in Utah to determine N mineralization rates. The N

mineralization rate was determined using the  $^{15}\text{N}$  isotope dilution technique. Reported net mineralization rates were  $0.25$  and  $0.48 \text{ mg (kg-soil)}^{-1} \text{ d}^{-1}$  with application of  $100$  and  $200 \text{ kg available N ha}^{-1}$  annually, respectively, for  $6$  years (Habteselassie et al., 2006).

Shi et al. (2004) incubated Nibley silty clay loam soil ( $0$ - $150$  mm depth) with dairy lagoon effluent for  $70$  d. The effluent contained  $130 \text{ mg/L}$  of org-N. They reported N mineralization of  $30\%$  and  $90\%$  with addition of  $100$  and  $200 \text{ mL effluent kg}^{-1}$  soil, respectively. The data showed the dependence of mineralization rate on application rate (Shi et al., 2004).

Crohn (2004) presented model predictions of total PAN of dairy lagoon effluent over a six-year period. Both inorganic N and mineralized N were included in the PAN calculation. Idealized steady state concept of amount of org-N was used in the model. The effect of temperature on mineralization rate was considered by temperature-adjusted time approach (summer days were stretched and winter days are contracted) (Crohn, 2004).

Zaman et al. (1999) incubated a Templeton sandy loam soil with dairy shed effluent to determine N mineralization. The soil was mixed with  $200 \text{ kg/ha}$  effluent. The N mineralization rate was determined using  $^{15}\text{N}$  dilution technique. The net mineralization rate was  $4 \text{ mg N (kg-soil)}^{-1} \text{ d}^{-1}$  after  $8$  days. Total net mineralization was calculated from graphs as  $16 \text{ mg (kg-soil)}^{-1} \text{ d}^{-1}$  after  $16$  days. From  $16$  to  $90$  days, mineralization rates and nitrification rates were nearly equal (Zaman et al., 1999).

Pomares-Garcia and Pratt (1978) applied cattle feedlot manure on sandy loam soil. Total N mineralization was calculated from the difference in final org-N in soil from added org-N

over a 10-month period. Average N mineralization of 40% and 17% was reported for dry sludge with 4% N and dry manure with 2% N, respectively.

The papers presented above showed high variability in org-N mineralization after application of manure. The variability could be due to dependence of mineralization on different conditions (factors), namely, protease activity, C:N ratio in effluent, temperature, moisture content, etc (Crohn 2004; Zaman et al. 1999).

#### 2.4. Ammonia Volatilization Modeling

Ammonia volatilization is governed by effluent properties, soil and surface properties (and conditions), environmental conditions, and the application method. Mathematical models can be used to predict NH<sub>3</sub> volatilization for a wide range of conditions. Models can also be used to check the sensitivity of a parameter to NH<sub>3</sub> volatilization.

Based on the models reported in the literature (not presented in this thesis), the one developed by Wu et al. (2003a) best represents the surface application of the hog lagoon effluent. The model uses physical principles, mass and energy balances, well established in literature, as governing equations. The equations are presented below (Wu and Nofziger, 2006):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K(\theta) \left( \frac{\partial h}{\partial z} - 1 \right) \right] - S(z, t) \quad [2.3]$$

$$C_h \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( K_h \frac{\partial T}{\partial z} \right) \quad [2.4]$$

$$\frac{\partial}{\partial t} \left[ \left( \rho_b K_d + \theta + (\theta_s - \theta) \frac{10^{pH} K_a K_H}{1 + 10^{pH} K_a} \right) C_{NHX(aq)} \right] = \frac{\partial}{\partial z} \left[ D \frac{\partial C_{NHX(aq)}}{\partial z} - q C_{NHX(aq)} \right] \quad [2.5]$$

Equation [2.3] (Darcy's Law) models effluent flow in soil profile, where  $\theta$  is the volumetric water content of the soil,  $t$  is time,  $z$  is depth,  $h$  is matric potential of the soil and  $S(z,t)$  is the sink term. The sink term,  $S(z,t)$  depends on the potential transpiration rate, maximum rooting depth of the plant,  $z$ , and matric potential at the depth  $h$ . Equation [2.4], the second law of heat conduction (Fourier's Law), simulates heat transfer in the soil profile. In eq. [2.4],  $C_h$  is the volumetric heat capacity of soil,  $T$  is soil temperature, and  $K_h$  is thermal conductivity;  $K_h$  is estimated from the thermal conductivity of the solids, water, and air in the soil and varied with soil temperature. The equation for the transport and transformation of TAN (Eq. [2.5]) in soil was derived from Fick's law;  $K_d$  is a combined partition coefficient of adsorption/desorption (depends on pH of soil),  $K_a$  is the equilibrium constant for  $\text{NH}_4^+$  to  $\text{NH}_3$  reaction,  $K_H$  (Henry's constant) is the partition coefficient for liquid-phase  $\text{NH}_4^+$ , partition coefficient for liquid-phase  $\text{NH}_3$  and partition coefficient for gaseous  $\text{NH}_3$ . In Eq. [2.5],  $D$  is the combined dispersion coefficient which depends on pH of soil,  $K_a$ ,  $K_H$ ; dispersion coefficients of  $\text{NH}_4^+$ , dissolved  $\text{NH}_3$  and gaseous  $\text{NH}_3$  in soil. The value of  $K_a$  used in the model was not mentioned either in Wu et al. (2003a) or in Wu and Nofziger (2006). For the initial and boundary conditions refer to Wu et al. (2003a) or Wu and Nofziger (2006). The value of another important parameter, the mass transfer coefficient for  $\text{NH}_3$  transport, is also not provided.

The model uses ponded-infiltration submodel to simulate flood irrigation (Wu et al., 2003a) and droplet volatilization submodel to simulate sprinkler irrigation (Wu et al., 2003b). The model was validated using surface application (flood irrigation) of hog anaerobic lagoon effluent. Wu et al., (2003) tested the numerical model against results from six field

experiments, following land application of hog lagoon effluent to bare soil by flood irrigation, conducted over a 3-year period (Warren, 2001; Zupancic et al., 1999). Both of the studies used passive flux samplers to measure  $\text{NH}_3$  concentrations. Three of the field experimental results showed very good fit for cumulative  $\text{NH}_3$  volatilization. The model over-predicted volatilization during July monitoring periods. Wu et al., (2003) attributed the discrepancy in July to the high wind speed during those periods, which might have caused the IHF method to underestimate the volatilization rate during the hours immediately after application, when the volatilization rate were the highest.

### 3. MATERIALS AND METHODS

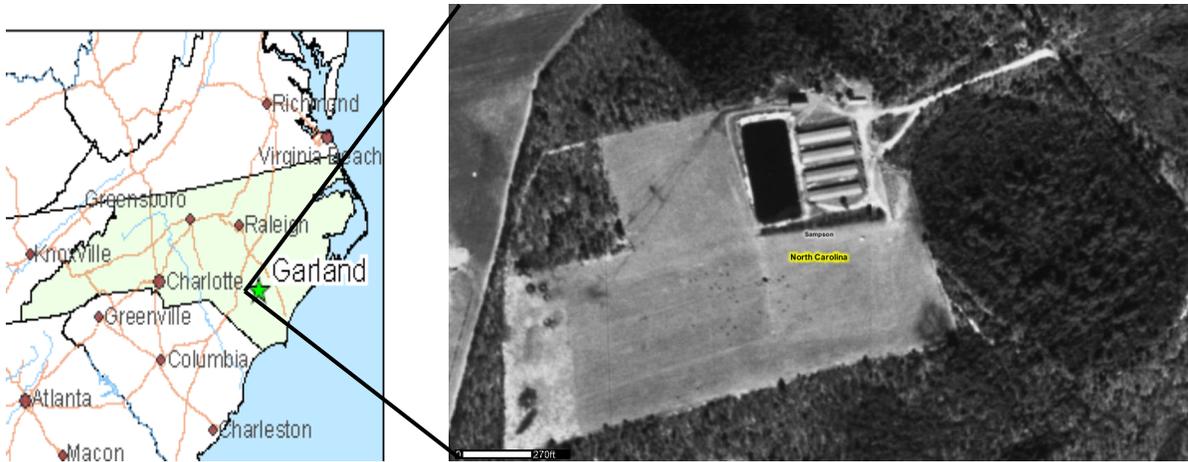
This chapter covers field studies and modeling. Ammonia concentrations and emissions measurement methods are explained. Methods used in determining soil properties used as input parameters for the NH<sub>3</sub> volatilization model (Wu et al., 2003a) as well as selection of input parameters for sensitivity analyses of the model are explained.

#### 3.1. Research Site and Soil Description

The field study was performed between October 2005 and July 2006. The research site and soil are described below.

##### 3.1.1. Description of research site

The research site (34.786° N, 78.394 ° W) is located in Garland, Sampson County, NC, about 150 km south of NC State University in Raleigh (Fig. 3.1). The land application site is part of a hog farm, owned by Mr. Alfred Smith. The hog farm consists of four finishing houses. Hog waste is collected in shallow pit beneath the slatted floor of the houses and flushed to an anaerobic lagoon. The land application site covers 13 ha. The entire area was planted to Coastal Bermudagrass (*Cynodon dactylon*) overseeded with oats and was also used for grazing cows.



**Figure 3.1. Location map of Garland, North Carolina and aerial view of the farm.**

### **3.1.2. Soil description**

The soil at the site is Cainhoy sand (Thermic, coated Typic Quartzipsamments) (NRCS, 1985). Selected physical and chemical properties of the soil as well as the methods used in their determination are listed in Table 3.1. The soil properties were required, for both characterizing the soil and as inputs for the  $\text{NH}_3$  emission model (Wu et al., 2003a). The soil properties were determined at the EAL (Environmental Analysis Laboratory, BAE), Soil Physical Properties Laboratory (SPPL) and Water Management Laboratory (WML), all at NC State University (NC SU). The bulk density and saturated hydraulic conductivity of soil were measured at the WML. Particle size distribution and the linear partition coefficient of the soil were determined at the SPPL, while all the soil chemical properties were determined at the EAL. For the initial soil chemical properties, multiple samples of the top 25 mm of soil were collected randomly from all over the site and composited in plastic bags before the start

of the study. The soil samples were then analyzed for total Kjeldahl nitrogen (TKN), NH<sub>3</sub>-N, NO<sub>3</sub>-N, moisture content and pH.

**Table 3.1. Selected measured and estimated properties of Cainhoy sand at the site**

Property	Value	Std.Dev.	Method used
Soil mineral composition <sup>1</sup>			Hydrometer method (Klute, 1986)
sand, %	93.3	1.3	
silt, %	3.1	1.3	
clay, %	3.6	0.0	
Soil textural class	Sand		USDA textural triangle
Bulk density <sup>2</sup> , g/cm <sup>3</sup>	1.30	0.05	Core sample
Saturated moisture content, %	26.7	1.3	
Saturated hydraulic conductivity <sup>3</sup> , cm/h	8.37	3.17	Constant head method (Klute, 1986)
TKN <sup>4</sup> , µg/g-dry soil	2700	1000	Persulfate Digestion, and NH <sub>3</sub> salicylate method for automated analysis (EPA Method 351.2, 1979)
TAN <sup>4</sup> , µg/g-dry soil	6.2	5.4	Ammonia salicylate method for automated analysis (EPA Method 351.2, 1979)
NO <sub>3</sub> -N <sup>4</sup> , µg/g-dry soil	10.7	4.0	Cadmium reduction method for automated analysis (EPA Method 353.2, 1979)
pH <sup>4</sup>	6.8	0.4	Electrometric Method (EPA Method 150.1, 1979)
Dispersivity <sup>5</sup> , cm	0.4	N/A <sup>6</sup>	RETC code (van Genuchten et al., 1991)
$\alpha$ <sup>5,7</sup> , cm <sup>-1</sup>	0.0135	N/A <sup>6</sup>	RETC code (van Genuchten et al., 1991)
n <sup>5,7</sup>	1.3830	N/A <sup>6</sup>	RETC code (van Genuchten et al., 1991)
NH <sub>4</sub> <sup>+</sup> partition coefficient	2.58	N/A <sup>6</sup>	Adsorption experiment (Sparks, 2003)

<sup>1</sup> Average of 2 samples

<sup>2</sup> Average of 4 samples

<sup>3</sup> Average of 6 samples

<sup>4</sup> Average of 5 samples

<sup>5</sup> Estimated from literature

<sup>6</sup> Not available

Table 3.1 (continued)

<sup>7</sup>  $\alpha$  and  $n$  are empirical constants affecting the shape of soil-water retention curve that is required for modeling. Both values were obtained from literature.

Most soil properties (e.g. soil texture) were determined by lab personnel from different labs. Some soil properties determined by the author for modeling purposes are briefly discussed below.

Saturated Hydraulic conductivity ( $K_s$ ): The constant head method was used to measure vertical  $K_s$  (Klute, 1986). Six undisturbed cores, selected randomly in the field, were used. The height and diameter of the cores were both 76.2 mm. Prior to saturation in a water bath, the bottom of each soil core was covered with a double layer of cheesecloth which was then retained in place with a rubber band. The cores were submerged to one-third height for 1 h (to prevent air entrapment) and later, to the full height for 42 h to saturate the cores. The time taken to discharge 80 mL of water from the cores was noted. Saturated hydraulic conductivity was calculated from Eq. [3.1]. The average of the six samples is presented in Table 3.1.

$$K_s = \frac{V}{A \times t} \cdot \frac{L}{\Delta H} \quad [3.1]$$

where,  $K_s$  = saturated hydraulic conductivity, m/s

$V$  = volume of water discharged through core,  $m^3$

$A$  = cross-sectional area of core,  $m^2$

$t$  = elapsed time to discharge  $V$   $m^3$  water, s

$\Delta H$  = Head difference (measured from water level to the bottom of core), m

L = height of soil core, m

Bulk density ( $\rho_b$ ): For bulk density of the top soil, four undisturbed 76.2 mm core samples were collected from random points in the field. The cores were dried in an oven for 24 h at 105°C. Weight of each core was taken after allowing it to cool to room temperature. The weight divided by volume of the core gave  $\rho_b$  (Klute, 1986). Mean  $\rho_b$  was calculated as the average of the  $\rho_b$  of the four samples.

Linear partition coefficient of  $\text{NH}_4^+$  (K): Three core samples, 0 - 76.2 mm depth, were collected from the traveling gun plot randomly; however, only the top 50.8 mm of the soil was used for the analyses. The soil was passed through a 2 mm sieve and mixed completely. First, the background  $\text{NH}_4^+$  concentration in the soil was measured. For this, 10 g of the soil was mixed with 100 mL of 2M KCl solution. The mixture was mechanically shaken for 30 minutes and then filtered. The filtrate was analyzed for  $\text{NH}_4^+$ . The air dried soil samples were oven dried for 24 h to determine the moisture content. The background  $\text{NH}_4^+$  concentration in the soil ranged 6.9 to 10.5  $\mu\text{g/g}$ -soil (oven dried basis) in the three samples with an average value of 8.8  $\mu\text{g/g}$ -soil.

After checking the range of  $\text{NH}_4^+$  ion concentration in the soil before and after land applications at the research site, it was decided to determine the partition coefficient for a range of 25 to 125  $\mu\text{g/g}$ -soil of initial  $\text{NH}_4^+$  concentrations in increments of 25  $\mu\text{g/g}$ . For this, 62.5  $\mu\text{g NH}_4^+/\text{mL}$  of  $\text{NH}_4\text{Cl}$  solution were prepared. First 10 mL of 0.001 M KCl was added to the soil sample in a centrifuge tube. Thereafter 0 (control), 4, 8, 12, 16 and 20 mL of the

NH<sub>4</sub>Cl solution were added to the soil samples to get 0, 25, 50, 75, 100 and 125 µg NH<sub>4</sub><sup>+</sup>/g-soil in triplicate. The suspension was allowed to settle for 60 min. The tubes were then centrifuged for 30 min to separate soil particles from the NH<sub>4</sub><sup>+</sup> solution. About 4 mL of the solution was extracted from the tube and analyzed for NH<sub>4</sub><sup>+</sup> concentration. It was assumed that the total NH<sub>4</sub><sup>+</sup> amount in the solution subtracted from total amount of NH<sub>4</sub><sup>+</sup> added to the soil gave NH<sub>4</sub><sup>+</sup> adsorbed to the soil. The partition coefficient (K) was obtained from the following equation (Sparks, 2003).

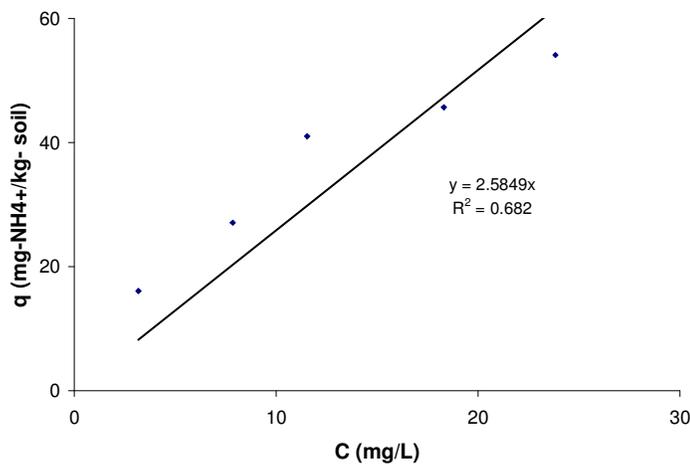
$$K = \frac{q}{C} \quad [3.2]$$

where, K = partition coefficient, mL/g

q = amount of NH<sub>4</sub><sup>+</sup> adsorbed in unit mass of dry soil, µg/g-dry soil

C = equilibrium NH<sub>4</sub><sup>+</sup> concentration, mg/L

The following plot was obtained from the data (Fig. 3.2). The partition coefficient was determined to be 2.58 mL/g.



**Figure 3.2. Linear adsorption isotherm of Cainhoy sand for NH<sub>4</sub><sup>+</sup>. Each point is an average of three replications.**

Although the Freundlich isotherm would have been a better fit for the plot (Fig. 3.2), the linear isotherm was used. This was because the model (Wu et al., 2003a) used only the linear isotherm to partition  $\text{NH}_4^+$  into soil-bound and solution phases.

### **3.2. Measurement of Environmental Parameters**

A weather station, four cup anemometers and a cup anemometer with wind vane (not in October 2005) were deployed in the field during monitoring to collect weather data. Two soil probes were deployed in the traveling gun plot to record soil temperatures during the May, June and July 2006 monitoring periods. The instruments, data collection and how the data were analyzed are discussed below.

#### **3.2.1. Weather station**

A weather station (Model 2900ET WatchDog) was deployed to collect the following hourly data (range and accuracy in parenthesis): wind speed (0 to 80 m/s,  $\pm 5\%$ ), wind direction ( $2^\circ$  increment,  $\pm 7^\circ$ ), air temperature (-20 to  $70^\circ\text{C}$ ,  $\pm 0.6^\circ\text{C}$ ), relative humidity (20 to 100%,  $\pm 3\%$ ), rainfall (tipping bucket rain gauge) (0.25 cm resolution,  $\pm 2\%$ ) and solar radiation (1 to  $1250 \text{ W/m}^2$ ,  $\pm 5\%$ ) (Source: Spectrum Technologies Inc.). Solar radiation data for the site were obtained for October 2005; for the other three monitoring periods, data from the Horticultural Crops Research Station at Clinton (about 30 km north of Garland) were used. Air temperature, relative humidity, and solar radiation obtained were also used as input parameters in  $\text{NH}_3$  emission model (Wu et al., 2003a). Air temperature was also used to correct flowmeter readings (discussed later). Rainfall data were used to observe the effect of

rainfall events on emissions. In October 2005, the wind direction data collected by the weather station wind vane was used to calculate NH<sub>3</sub> emission (discussed later).

### **3.2.2. Wind speed and direction**

Four 3-cup anemometers (Onset HOBO S-WSA-M003; range: 0 to 45 m/s; accuracy:  $\pm 1.1$  m/s; resolution: 0.38 m/s) were used to record wind speeds at different heights. One anemometer with wind vane (Onset HOBO S-WCA-M003; range: 0 to 44 m/s and 0 to 358°) was used for wind speed and wind direction measurements at 2.2 m height. The accuracy and resolution of the S-WCA-M003 anemometer were  $\pm 0.5$  m/s and 0.19 m/s, respectively; the wind vane had an accuracy of  $\pm 5^\circ$  and resolution of  $1.4^\circ$ , respectively. Beginning May 2006, wind direction measurements were made with the S-WCA-M003 due to its higher accuracy and resolution than the weather station anemometer-wind vane combination used in October 2005. In October 2005, only S-WSA-M003 anemometers were used. The S-WSA-M003 and S-WCA-M003 anemometers were deployed with a sampling interval of 1 s and logging interval of 10 min. As indicated on the brochures of both anemometers and Hoboware Pro® software, it appeared that data collected at every sampling interval was averaged and logged in the HOBO data logger every logging interval. Accordingly, the data logger was programmed to sample wind speed every second and log the averaged wind speed every 10 min. However, according to HOBO®, only the S-WCA-M003 anemometer had the sampling feature (the fact came to the author's attention only on August 2, 2007). The S-WSA-M003 anemometers were, thus, taking readings every 10 min and logging it.

Hence, during May, June, and July 2006, the wind speed profiles were calculated using two methods. In method-I, the 10-min corrected (discussed later) wind speed values obtained using the S-WSA-M003 anemometers at 0.2, 0.6, 1.2, and 3.4-m heights were plotted and the wind speed at 2.2-m was obtained through interpolation (see Results and Discussion). In July 2006, when the wind speed data at the 3.4-m height was lost due to breakage of the signal wire (not detected until the study ended), wind speed values at 2.2 and 3.4-m heights were obtained through extrapolation of the wind speed profile based on the data obtained from the lower three anemometers. In method-II, the corrected (discussed later) wind speed measurements of the S-WCA-M003 anemometer deployed at 2.2 m height were used to calculate the wind speeds at all other heights using the logarithmic profile (Eq. [3.3]) (Rosenberg et al., 1983) based on assumptions of neutral stability.

$$\frac{U_2}{U_1} = \frac{\ln(z_2 - d) - \ln z_o}{\ln(z_1 - d) - \ln z_o} \quad [3.3]$$

where,  $U_1$  (known) and  $U_2$  are wind speeds (m/s) at heights (m)  $z_1$  and  $z_2$ , respectively;  $d$  is zero plane displacement height (m) and  $z_0$  is roughness parameter, m. The term  $d$  (m) is given by the Eq. [3.4] and  $z_0$  is calculated from Eq. [2.2].

$$\log_{10} d = 0.979 \log_{10} h - 0.154 \quad [3.4]$$

where,  $h$  is the height of the crop (m).

Dr. S. P. Arya, professor in the Department of Marine, Earth and Atmospheric Sciences (NCSU), told the author on several occasions in 2006 and 2007 that assuming neutral stability was safe for low heights (up to 5 m) and large area without any obstructions (e.g. trees) to modify the wind profile. Recently, Ro and Hunt (2007) showed that the logarithmic

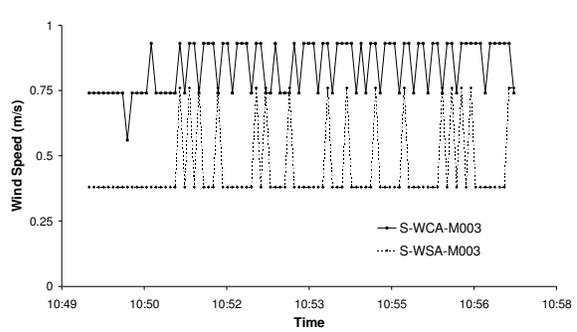
profile effectively described vertical wind speed variations, irrespective of stability conditions. For October 2005 monitoring period, method-I was used.

Since the S-WCA-M003 anemometer, placed at 2.2 m height, consistently gave higher wind speed than S-WSA-M003 anemometer placed at 3.4 m height, both were sent to the manufacturer for evaluation. The manufacturer reported that both anemometers worked as per specifications. Since the discrepancies in the field readings were disturbing, it was decided, *post hoc*, to recalibrate both anemometers in the Mechanical and Aerospace Engineering (MAE) Department's wind tunnel. All the wind speeds recorded in the field during the monitoring periods at 2.2 m and 3.4 m heights ranged from 0 to 5 m/s. The two anemometers (one each of S-WSA-M003 and S-WCA-M003) were placed in a fixture that held both anemometers upright in the wind tunnel (Fig. 3.3). Wind speeds in the wind tunnel were varied from 1 to 5 m/s in the following order: 1, 2, 3, 4, 5, and 1.5 m/s. The flow regime in the wind tunnel became unstable at wind speeds below 1 m/s as indicated by the rapidly fluctuating wind speed values; hence, 1 m/s speed was used as the starting wind speed. The wind speeds were kept constant for 10-15 minutes. Both anemometers were connected to a HOBO data logger and data was recorded every 5 s.

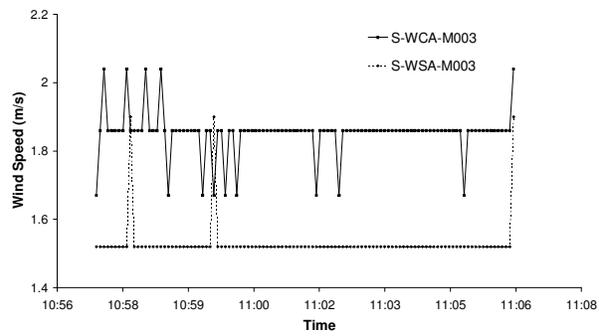


**Figure 3.3. Arrangement of two anemometers in wind tunnel.**

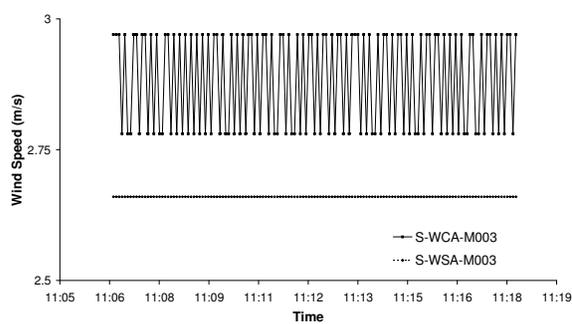
Both anemometers recorded consistently lower wind speed than that shown by the wind speed measurement system in the wind tunnel (Fig. 3.4). The MAE wind tunnel recorded pressure differential and used Bernoulli's equation to calculate wind speeds in the tunnel which was more accurate and precise than the two anemometers.



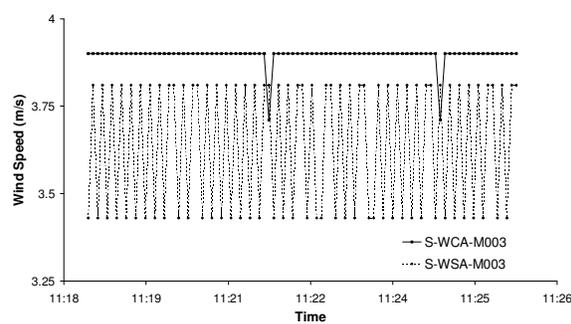
(a) 1 m/s



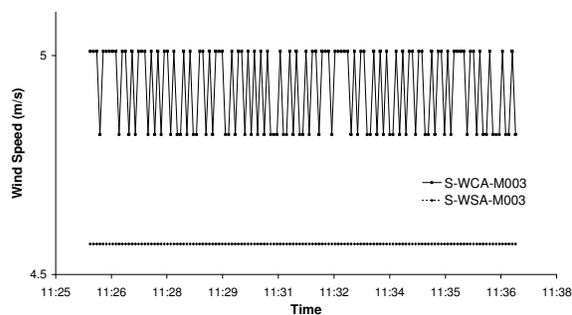
(b) 2 m/s



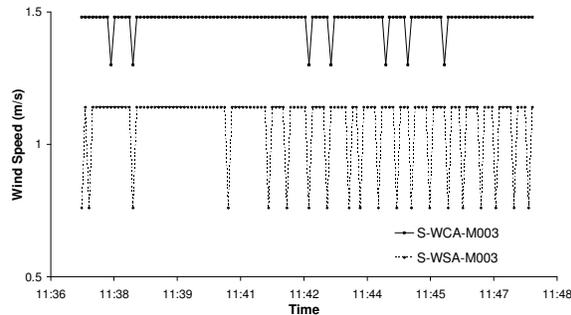
(c) 3 m/s



(d) 4 m/s



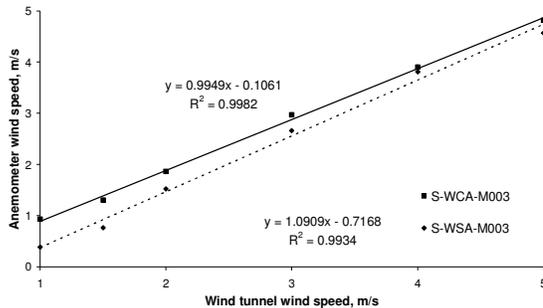
(e) 5 m/s



(f) 1.5 m/s

**Figure 3.4. Results of the evaluation of two anemometers in the wind tunnel at different wind speeds. The oscillation range shown by the anemometers is the instrument resolution (Note the lower resolution of S-WCA-M003).**

The calibration curves (Fig. 3.5) were obtained from the wind tunnel experiment. The calibration curves were used to correct wind speeds (if > 0 m/s) for the two anemometers.



**Figure 3.5. Calibration curves for wind speeds of the two anemometers (S-WSA-M003 and S-WCA-M003).**

Wind rose diagrams were prepared from wind directions and speeds, corrected or calculated (in October 2005) at 2.2 m height for all monitoring periods (see Results and Discussion for details). The wind directions were divided into 16 sectors: N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW. Wind directions between 348.75 to 11.25° were taken as North (N) direction and so on. The frequency (every 10 min) of wind in one direction was multiplied with the averaged wind speed in that direction and expressed as percentage for all monitoring periods. The wind rose was plotted in a 360° circle showing 16 directions, and the lengths of lines corresponding to the percentages in each direction in AutoCAD 2006.

### 3.2.3. Soil temperature

The soil temperatures were recorded in the traveling gun plot during May, June and July 2006 monitoring periods. Two soil temperature probes (TMC6-HD) were deployed and

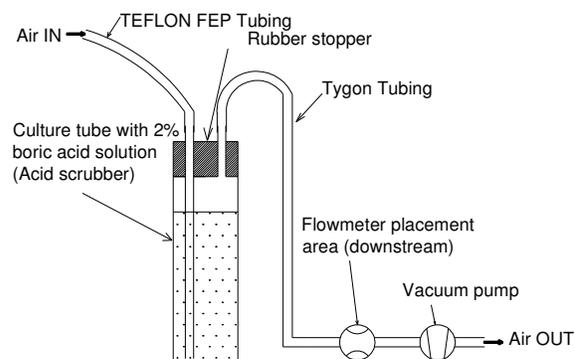
connected to a data logger (HOBO U12). The logger recorded averaged soil temperatures every 10 min. The soil temperatures were compared with modeled soil temperatures.

### **3.3. Ammonia Emission**

Ammonia concentration measurements using acid scrubbers are explained below. Also, NH<sub>3</sub> emissions estimation using the IHF method is discussed.

#### **3.3.1. Scrubber description**

Acid scrubbers were used to measure NH<sub>3</sub> concentration during and after land applications. A 100 mL glass culture tube was used as an acid scrubber. It was filled with about 70 mL of 2% boric acid solution (3% solution was used in October 2005) to trap NH<sub>3</sub>-N in the air passing through it. The scrubber was fitted with a two-hole rubber stopper. Air was brought in through Teflon FEP (Fluorinated Ethylene Propylene) tubing (from a certain height above the ground) and the NH<sub>3</sub> in the air was scrubbed by the boric acid solution and converted to ammonium borate. The scrubbed air was pulled out through the other hole in the stopper by a vacuum pump (Gast Manufacturing Inc., Miniature Diaphragm 10D 1125 Series, 4.3 Lpm) (Fig. 3.6).



**Figure 3.6. The scrubber system.**

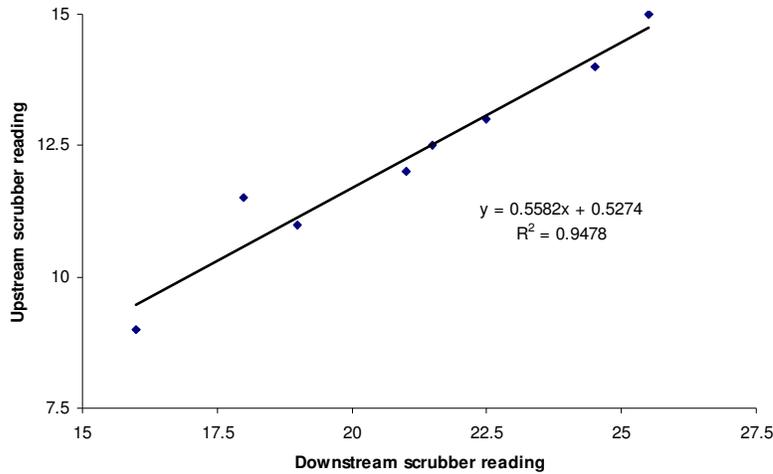
The  $\text{NH}_3$  trapping efficiency of an identical acid scrubber was  $>99\%$  (Shah et al., 2006). The scrubber assembly included a computer fan to prevent the voltage regulator from overheating. Holes were made on the sides of the containers to facilitate airflow and to prevent excessive heating. The vacuum pumps and fan were powered by two 12-V automotive batteries connected in parallel (only one battery was used in October 2005). Two batteries were provided to ensure continuous operation of the scrubber assembly, even if one battery failed. The assembly was protected from the weather by placing it on a cart and covering with an inverted plastic container. The batteries were charged by a 15-W solar panels (12 V, 1 A) placed on top of the container.

### **3.3.2. Ammonia concentration calculation**

Ammonia concentration in the air passing through the acid scrubber was calculated from the amount of TAN in the scrubber and total air flow during a sampling period. The TAN concentration in the scrubber solution was measured using the auto-analyzer in the EAL. The

volume of acid solution in the scrubber was also noted. To determine the volume of air passing through the scrubber, the air flow-rate was measured at the beginning and end of monitoring period with a flowmeter (Gilmont Instruments, Industrial Flowmeter GF-8321-1401, 0.8-6 L/min,  $\pm 5\%$ ). At the end of a monitoring period, after noting the readings on the flowmeter, the scrubbers were replaced with scrubbers with fresh boric acid solution.

Flowmeter readings were recorded at the start and end of a monitoring period and the average of the two readings was taken as the average flowmeter reading for the entire monitoring period. Using the calibration curve provided by the flowmeter manufacturer, the average airflow rate was calculated from the average flowmeter reading. The flowmeter was placed downstream of the scrubber in October 2005 and May 2006 monitoring periods. The downstream airflow measurements results in overestimation of flow rates (Shah et al., 2007). The pressure at the downstream would be lower due to vacuum pump, which would cause the air volume to be higher. The volume of air we want would be the volume at atmospheric pressure, which would be obtained by taking upstream reading. To correct for the air flow rate, *post hoc*, two identical flowmeters were placed upstream and downstream of an acid scrubber in the lab. The air flowrates were generated corresponding to 15 to 25 units on the downstream flowmeter. Both downstream and upstream flowmeter readings were plotted (Fig. 3.7) to obtain a calibration curve for correcting the flowmeter readings. In June and July 2006, the flowmeter was placed upstream of the scrubber, and hence, no correction was required.



**Figure 3.7. Downstream vs. upstream flowmeter readings.**

After correcting for flowmeter location (when required), the airflow rate was corrected for temperature using the Gas Law (Eq. [3.5]). This correction was required since the flowmeter had been calibrated by the manufacturer at 21.1°C.

$$Q_{ac} = \frac{(21.1 + 273.16)}{T + 273.16} \cdot Q_a \quad [3.5]$$

where,  $Q_{ac}$  = corrected air flow rate,  $m^3/s$

$Q_a$  = air flow rate from Gilmont calibration curve,  $m^3/s$

$T$  = ambient air temperature during the sampling period, °C

Ammonia-N in the sampled air was calculated using the following equations.

$$M_g = C_g \times V_g \quad [3.6]$$

$$V_g = Q_{ac} \times t \quad [3.7]$$

$$C_g = \frac{M_g}{V_g} \quad [3.8]$$

where,  $M_g$  = mass of  $\text{NH}_4^+$ -N ions in the scrubber solution (mg),

$C_g$  = TAN concentration in the scrubber solution (mg/L),

$V_s$  = volume of scrubber solution (L),

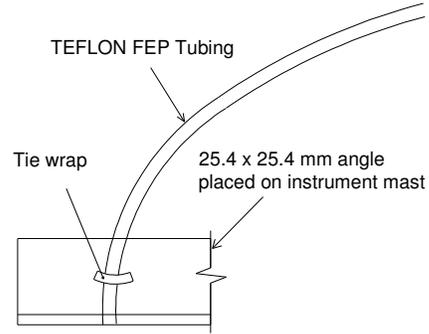
$V_g$  = volume of air passed through the scrubber during a sampling period ( $\text{m}^3$ ),

$Q_{ac}$  = average flow rate of air through the scrubber ( $\text{m}^3/\text{min}$ ),

$t$  = duration of a sampling period (min), and

$C_g$  = average TAN concentration in air during a sampling period ( $\text{mg}/\text{m}^3$ ),

Three masts (background, traveling gun and drag hose), each with five arms at fixed heights were used to collect air samples. The masts had arms at the heights of 0.2 m, 0.6 m, 1.2 m, 2.2 m and 3.4 m from the ground surface. The background mast had two sets of arms, one for tubing and other for anemometers (Fig. 3.8 (a)). The tubing was placed facing down on the arm as shown in Fig. 3.8 (b). This arrangement was done to reduce chances of effluent mist from entering the scrubber and affecting TAN collected during 0-4 h monitoring period in the traveling gun plot.



(a) Background mast with anemometers      (b) Tubing arrangement for air sampling

**Figure 3.8. Mast showing tubing arrangement and anemometers.**

### 3.3.3. Ammonia emission measurement

Ammonia emission was measured using a modification of the integrated horizontal flux (IHF) method (Eq. [2.1]).

$$\Phi = \frac{1}{x} \sum_{k=1}^5 C_k \cdot u_k \cdot \Delta z_k \quad [3.9]$$

where,  $C_k$  = average  $\text{NH}_3\text{-N}$  concentration at a particular  $k$  for a sampling duration ( $\text{mg}/\text{m}^3$ ),

$u_k$  = average wind speed at height  $z_k$  (m/s),

$$\Delta z_1 = \Delta z_2 = 0.4 \text{ m}$$

$$\Delta z_3 = 0.8 \text{ m}$$

$$\Delta z_4 = \Delta z_5 = 1.2 \text{ m}$$

The  $C_k$  and  $u_k$  values measured or calculated at 0.2 ( $z_1$ ), 0.6 ( $z_2$ ), 1.2 ( $z_3$ ), 2.2 ( $z_4$ ), and 3.4 ( $z_5$ ) m from the soil surface. The  $\Delta z$  values were calculated as follows:  $\Delta z_1$  was taken as twice the height from 0 to 0.2 m, and  $\Delta z_2$  was twice the height from the upper limit of  $\Delta z_1$  to  $z_2$ . Similarly,  $\Delta z_3$ ,  $\Delta z_4$ , and  $\Delta z_5$  were calculated. Hence the Eq. [3.9] integrated horizontal  $\text{NH}_3$  flux over 4 m vertical plane. The equation may have underestimated the flux when the concentration boundary layer extended beyond 4 m height, probably under unstable conditions. The height of the boundary layer was checked for each monitoring period by assuming 10% of concentration at 0.2 m height as ambient  $\text{NH}_3$  concentration.

The fetch ( $x$ ) for the traveling gun plot was taken as the wetted radius of the field. During each application, the wetted radii in the north, east, south and west quadrants were marked four times during the application (every 15-20 min). The averaged value of all the distances was taken as the wetted radius during that application. For the drag hose plot,  $x$  was calculated as the length the air had traveled on the treated plot. The length was obtained from the averaged mean hourly wind direction of that monitoring period and geometry of the plot.

Background  $\text{NH}_3\text{-N}$  concentrations were measured to adjust the  $\text{NH}_3$  concentrations in the treated plots for background sources (e.g., lagoon, cow patties or from one treatment on the other), if necessary. The deduction could only be done when the wind rose diagrams (described later) indicated that the background and the treated plots'  $\text{NH}_3\text{-N}$  concentrations were equally (more-or-less) affected by ambient  $\text{NH}_3$  concentrations. There were times when the traveling gun plot seemed to affect only the background mast (according to the wind rose diagram) but not the drag hose plot (as it was farther away); under those conditions, the background  $\text{NH}_3\text{-N}$  concentration was not deducted from either the traveling gun or the drag

hose plot  $\text{NH}_3\text{-N}$  concentrations. When both plots and the background  $\text{NH}_3\text{-N}$  concentrations seemed to be affected by the lagoon, hog house, or cow manure in the plots, the background concentration was deducted from both the traveling gun and drag hose  $\text{NH}_3\text{-N}$  concentrations. The author acknowledges this to be a weakness of this method since during a sampling duration, due to change in wind direction, the background must could be affected by both treatments as well as the lagoon. However, the need to compare emissions from two treatments necessitated their locations close to one another.

Since there were two methods (I and II) for calculating the wind speed profiles, ammonia emissions were calculated using both methods. Ammonia emissions, calculated using method-II, were considered to be more reliable because the logarithmic profile effectively described the wind speed profile, irrespective of stability conditions (Ro and Hunt, 2007).

During land application with the traveling gun, the effluent mist was being sucked into the higher elevation scrubbers (higher than 0.6-m) during the 0-4 h period. Hence, the concentrations at the higher elevations were estimated through extrapolation of the logarithmic profile (Denmead, 1983) (Refer to Section 3.4. Land Application).

### **3.4. Land Application**

Hog anaerobic lagoon effluent was land applied using a traveling gun and drag hose systems (within 2 h of one another) in fall (October 2005), spring (May 2006), and summer (July 2006). In June 2006 (summer), lagoon effluent was land applied using only the traveling gun.

The drag hose system had an application width of 2.4 m (in July 2006, a 3.0-m wide unit was used). The application rate of the drag hose was about 0.9 m<sup>3</sup>/min. The drag hose unit had an aerator (make: Aerway) that preceded the application unit. Hence, a portion of the effluent moved into the soil as soon as it was applied. The traveling gun (Nelson 150 series) had a 27.4 mm ring nozzle and was operated at 414 kPa (60 psi). In this study the traveling gun was kept stationary at the center of a circular plot and the gun was allowed to rotate 360°. The traveling gun had a wetted radius of the about 90 m.

Four effluent samples were collected each day of tests from the top 0.3 m of the lagoon before each application. The samples were collected using a lagoon sampler from edge of the lagoon, after removing the crust. The samples were stored in labeled plastic bottles and brought to the EAL in a cooler. The samples were analyzed for TKN, TAN, chloride (Cl), and pH. The analytical methods used are presented in Table 3.2. The analytical results are presented in Table 3.3.

**Table 3.2. Analytical methods used by the BAE Environmental Analysis Laboratory (EAL)**

Parameter	Method used	Reference
TKN	Persulfate Digestion, and ammonia salicylate method for automated analysis	EPA Method 351.2 (1979) with slight modifications including dialysis or Standard Methods 4500-NH <sub>org</sub> B (1998)
NH <sub>3</sub> -N	Ammonia-salicylate method for automated analysis.	EPA Method 351.2 (1979) or Standard Methods 4500-NH <sub>3</sub> G (1998), with slight modifications including dialysis

Table 3.2 (continued)

NO <sub>3</sub> -N	Cadmium reduction method for automated analysis	EPA Method 353.2 (1979), Technicon Industrial Method No. 100-70W (1973), or Standards Methods 4500-NO <sub>3</sub> -E (1998) with slight modifications including dialysis
Cl <sup>-</sup>	Ferricyanide method for automated analysis	EPA Method 325.2 (1979) or Standard Methods 4500-Cl <sup>-</sup> -E (1998) with slight modifications including dialysis
pH	Electrometric Method	EPA Method 150.1 (1979) or Standard Methods 4500-H <sup>+</sup> B pH Value (1998)

**Table 3.3. Effluent characteristics<sup>1</sup> for each monitoring period.**

Parameters	Oct 2005	May 2006	June 2006	July 2006
TKN, mg/L	531 (17)	818 (8)	810 (28)	618 (31)
NH <sub>3</sub> -N, mg/L	432 (5)	756 (8)	706 (10)	566 (8)
Cl <sup>-</sup> , mg/L	543 (1)	639 (3)	638 (13)	661 (5)

<sup>1</sup> Mean (standard deviation) of four samples

The total amount of effluent applied in each monitoring period was determined from the starting and ending flowmeter reading; the propeller-type flowmeter was installed upstream of the traveling gun or drag hose unit. The volume of effluent applied using the traveling gun was also calculated by estimating the flow rate (from the manufacturer’s chart) based on pressure at the nozzle and duration of application.

Details on land application are presented below. Drift and evaporation measurements are discussed in the subsequent section.

### 3.4.1. October 2005

Land application was done on 17 October 2005 by the traveling gun and drag hose (Fig. 3.9) by S. B. Shah, G. L. Grabow, and P. W. Westerman of the BAE Department. Ammonia

concentrations were measured for 120 h. Average wetted diameter of the traveling gun plot was calculated as 82.30 m with application starting at 10:35 AM and ending at 12:05 PM. The gun nozzle pressure was 414 kPa and the corresponding flowrate was 0.69 m<sup>3</sup>/min. The drag hose applied effluent on a 31.7 × 31.7 m area beginning at 1:20 PM for a total of 10 min. Efforts were made to apply the same depth of effluent to both plots. The actual depths of application (based on flowmeter reading) applied with the traveling gun and drag hose were 11.2 and 12.4 mm, respectively.

Four effluent samples each were obtained from both treatments. The traveling gun samples were obtained from near the nozzle and drag hose from near the shroud. The samples were analyzed for TAN, TKN, Cl<sup>-</sup>, and pH.

In the case of the traveling gun, the system for monitoring NH<sub>3</sub> concentration (mast) was located <10 m from the gun and was turned on at the same time as the gun. The mast was believed to be kept at safe distance so as not to gather any effluent mist directly from the gun nozzle. However, it seemed that some amount of mist may have been sucked into the scrubber. After considering the mist formation and subsequent actions of wind, gravity, buoyancy and inertia on the mist droplets, it was assumed that the 0.2 m sampling height would be least likely to be affected by the mist phenomenon. Hence, uncertainty of mist accumulation in the scrubbers increased with height. It was decided to check the ratio of NH<sub>3</sub> concentrations of all other four heights vs. the 0.2 m height concentrations for 0-4 h duration and 4-24 h duration (when there is no problem of mist being sucked in) for traveling gun mast. The assumption for this was that, if no mist entered the scrubber at a particular height, the ratio of ammonia concentrations at a particular height vs. 0.2 m at 0-4 h would be similar

or lower than the corresponding ratio for the 4-24 h period. This assumption was based on the premise that ammonia concentration declined logarithmically with height over a flat surface (Denmead, 1983) but would retain similar trends for different periods. The log profiles of NH<sub>3</sub> concentration were developed from the heights “unaffected” by the mist. The profiles were then, extended to calculate the “likely” NH<sub>3</sub> concentrations at higher heights. This approach was also used for the other periods.

After the application was completed, the gun was moved outside of the plot and the monitoring system was moved to the center of the plot. In the drag hose, the mast was placed outside the plot and moved to the center of the plot immediately after the application. The monitoring durations were: 0-4 h, 4-24h, and every 24 h thereafter for a total of 120 h.

#### **3.4.2. May 2006**

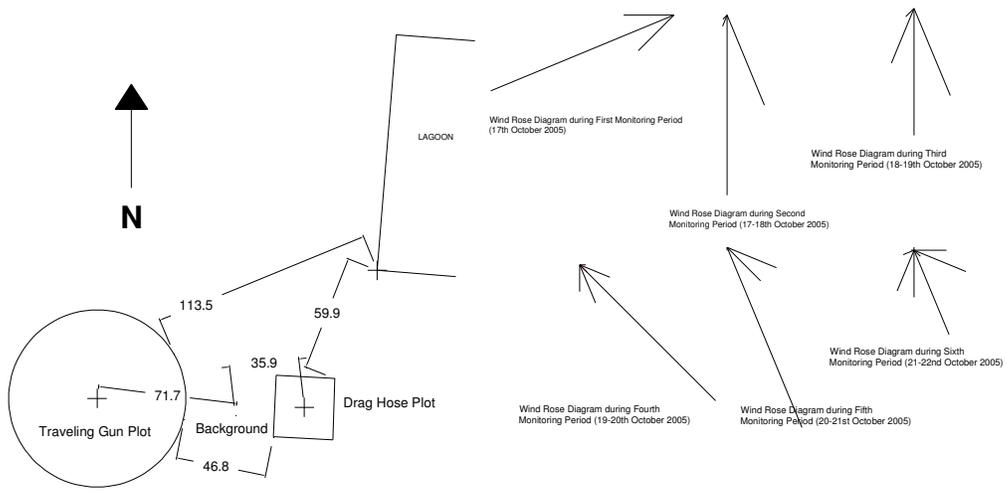
Effluent was applied on 15 May 2006, on drag hose plot and traveling gun plot (Fig. 3.9). The drag hose plot was rectangular measuring 31.7 × 56.1 m; application started at 10:30 AM and ended at 11:00 AM. The traveling gun application started at 11:57 AM and ended at 12:59 PM; the average wetted diameter was calculated as 71.93 m. The actual depths of application (based on flowmeter reading) applied with the traveling gun and drag hose were 10.8 and 10.4 mm, respectively. The NH<sub>3</sub> sampling data for the 4-24 h period on traveling gun plot were lost as the vacuum pumps were not running at the end of the monitoring period.

The effluent sampling was done as in October 2005. Soil sampling was done for bulk density using core samplers, the height and diameter of which were both 76.2 mm. The top

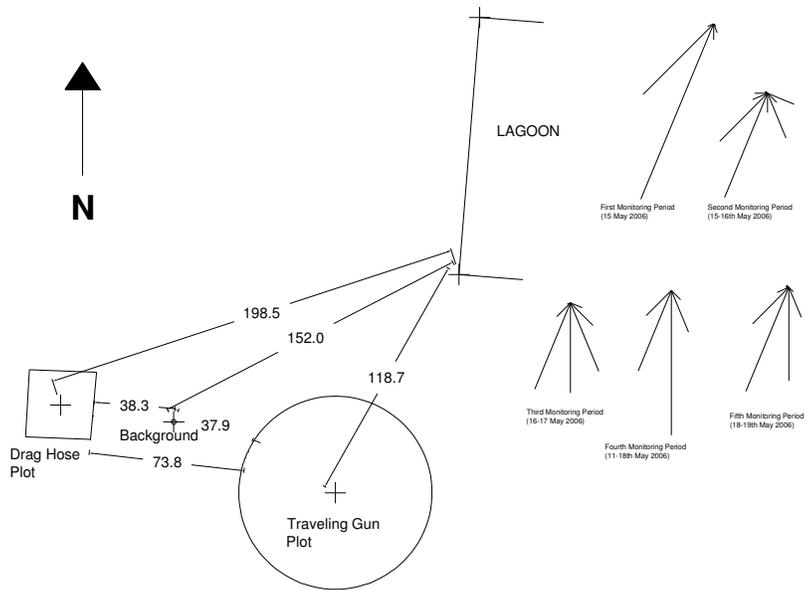
380 mm of soil were collected with soil probes and composited in plastic bag before and after application in plot applied with traveling gun to analyze for TKN, TAN,  $\text{NO}_3^-$ -N, moisture content and pH.

Since the 2.2 and 3.4 m scrubbers likely pulled in some mist during application, as in October 2005, a logarithmic profile had to be developed based on concentration ratios described earlier. However, since there was no 4-24 h data available for the traveling gun, the 0-4 h ratios were compared with 4-24 h ratios for other application periods.

**Figure 3.9. Layout of the traveling gun and drag hose plots with wind rose diagrams for the 0-4 and 4-24 h monitoring periods for October 2005 and May 2006 (all dimensions are in m).**



(a) Plot layout for October 2005 Monitoring Period



(b) Plot layout for May 2006 Monitoring Period

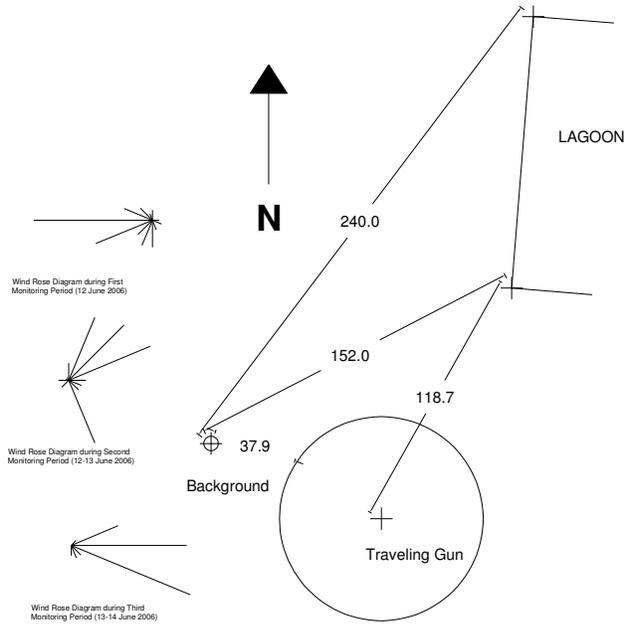
### **3.4.3. June 2006**

Only the traveling gun was used for land application on 12 June 2006 (Fig. 3.10). This application was not planned before; it was done to compensate for the loss of data during 4-24 h monitoring period in plot applied with traveling gun. Application started at 10:48 AM and ended at 11:43 PM. The actual depth of application (based on flowmeter reading) applied was 8.5 mm. Monitoring for  $\text{NH}_3$  concentrations was stopped on 14 June due to the approaching tropical storm 'Alberto' allowing for only 48 h of monitoring. All other activities were same as May 2006 traveling gun land application; however, the concentration profile was modified using the approach using in October 2005.

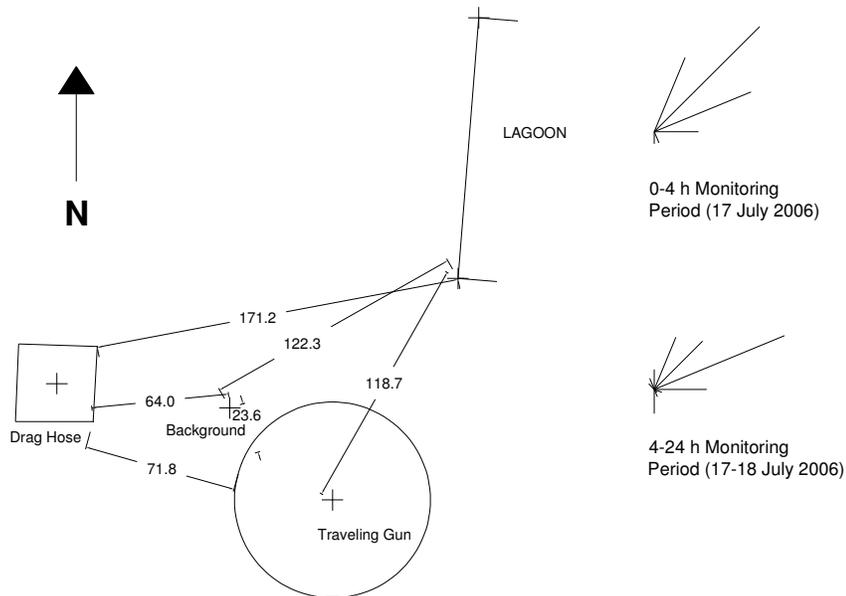
### **3.4.4. July 2006**

Effluent was applied on 17 July 2006 using the traveling gun and drag hose systems (Fig. 3.10). Monitoring was done until 21 July (96 h). The drag hose plot was square with 36.6-m sides; application started at 10:26 AM and ended at 10:44 AM. The traveling gun plot diameter was 87.33 m; application started at 11:18 AM and ended at 12:48 PM. The actual depths of application (based on flowmeter reading) applied with the traveling gun and drag hose were 10.1 and 10.4 mm, respectively. During this application, the scrubber solution in the 3.4-m height was discolored which showed that the mist affected the scrubbers located at the higher locations which required correction using the logarithmic concentration profile similar to what was done in June 2006. All other activities were the same as during the May 2006 land application.

**Figure 3.10. Layout of the traveling gun and drag hose plots with wind rose diagrams for the 0-4 and 4-24 h monitoring periods for June 2006 and July 2006 (all dimensions are in m).**



(c) Plot layout for June 2006 Monitoring Period



(d) Plot layout for July 2006 Monitoring Period

### 3.4.5. Drift and evaporation calculations

To determine evaporation,  $\text{NH}_3\text{-N}$  and drift loss during application by traveling gun, 16 catch cans were placed along the east-west axis and 16 more along the north-south axis. The catch cans were spaced 6.1 m apart to cover a circle of 91.5-m diameter. Alternate catch cans were filled with 50 mL 2% boric acid solution to trap  $\text{NH}_3\text{-N}$  in the effluent (Fig. 3.11). Empty catch cans were placed to measure pH of effluent caught; the liquid were discarded after pH measurement in the field. Depths collected in catch cans outside of the wetted radius (discussed earlier) was distributed evenly to catch cans within the circle. Depth of application within the wetted radius was calculated by taking the mean of those catch cans depths. Four catch cans, with 50 mL 2%-boric acid solution, were placed on the outside perimeter of 91.5 m diameter to check amount of background  $\text{NH}_3$  deposition (if any), in May, June and July 2006.



**Figure 3.11. Arrangement of catch cans in the traveling gun plot before land application**

Upon completion of effluent application, the effluent collected in the catch can with boric acid solution was transferred to a labeled bottle to be analyzed in EAL for TKN, TAN, and Cl<sup>-</sup>. Using the Cl<sup>-</sup> concentration in the catch can and gun nozzle, evaporation loss from nozzle to ground (Till, 1957; McLean 2000) was calculated as:

$$E(\%) = \frac{(C_{Cl^-})_{can} - (C_{Cl^-})_{nozzle}}{(C_{Cl^-})_{can}} \cdot 100 \quad [3.10]$$

where, E = evaporation, (%)

$(C_{Cl^-})_{can}$  = average Cl<sup>-</sup> concentration in catch cans (mg/L)

$(C_{Cl^-})_{nozzle}$  = Cl<sup>-</sup> concentration in nozzle (mg/L)

The drift was calculated from mass balance of the effluent. The depth of effluent applied was deducted from depth of effluent collected in catch can and evaporation (Eq. [3.10]).

$$D = \left( \frac{d_a - d_{can}}{d_a} \right) \cdot 100 - E \quad [3.11]$$

where, D = drift (%);  $d_a$  and  $d_{can}$  are depths of effluent applied (flowmeter data) and average depth of effluent collected in catch cans, respectively.

#### 3.4.6. Ammonia emission during application from the traveling gun

Ammonia-N loss ( $TAN_{loss}$ , %) between the traveling gun nozzle and the ground was calculated by mass balance of TAN as shown below:

$$(TAN_{loss})\% = \frac{d_a (TAN)_{nozzle} - d_{can} (TAN)_{can}}{d_a (TAN)_{nozzle}} \cdot 100 \quad [3.12]$$

where,  $(\text{TAN})_{\text{nozzle}}$  is average TAN concentration of four effluent samples taken from gun nozzle;  $(\text{TAN})_{\text{can}}$  is weighted average TAN concentration in catch cans. It may be noted that Eq. [3.12] accounted for both, evaporation and drift.

### 3.5. Plant-available Nitrogen (PAN)

The PAN was calculated as follows:

$$PAN = (1 - A) \cdot \frac{[TAN]}{[TKN]} + B \cdot \left(1 - \frac{[TAN]}{[TKN]}\right) \quad [3.13]$$

where, A is  $\text{NH}_3\text{-N}$  emission as fraction of TAN and B is fraction of mineralizable N (0.5) (Barker, 1994).

### 3.6. Sensitivity Analysis of $\text{NH}_3$ Emission Model

Sensitivity analysis of the  $\text{NH}_3$  emission model was done for the following parameters: TAN concentration of effluent, soil pH, effluent pH, linear partition coefficient (for  $\text{NH}_4^+\text{-N}$ ), and wind speed. The baseline values for each are presented in Table 3.4 for each monitoring periods. The sensitivity analysis was based on relative sensitivity ( $S_r$ ) concept (James and Burges, 1982).

$$S_r = \frac{\frac{O_N - O_B}{O_B}}{\frac{I_N - I_B}{I_B}} \quad [3.14]$$

where,  $O_N$  and  $O_B$  are new and baseline outputs ( $\text{NH}_3$  emission), respectively; and  $I_N$  and  $I_B$  are new and baseline input values, respectively.

**Table 3.4. Parameters used in the sensitivity analysis of the ammonia emission model, their baseline values and change from baseline values.**

Parameter	Baseline value	% increase	% decrease
Total ammonical-N, mg/L	562	20	20
Soil pH	7.25	50	50
Linear partition coefficient, cm <sup>3</sup> /g	2.58	75	75
Wind speed, m/s		50	50

The sensitivity of the model, to the input parameter in question, was categorized according to  $S_r$  as follows:  $S_r < |0.01|$  insensitive,  $|0.01| \leq S_r < |0.10|$  slightly sensitive,  $|0.10| \leq S_r < |1.00|$  moderately sensitive,  $|1.00| \leq S_r < |2.00|$  sensitive, and  $S_r \geq |2.00|$  extremely sensitive. Wu et al. (2003a) did the sensitivity analyses on air temperature, wind speed, soil texture and soil pH. They reported the sensitivity of the model as moderately sensitive for air temperature and wind speed.

The TAN concentration in the effluent is directly related to the amount of  $\text{NH}_3$  available for volatilization. Hence, the model's sensitivity to TAN provides a reliable indication of the amount of  $\text{NH}_3$  emission. Emission would be expected to increase with soil pH since higher pH soil would favor the dissociation of  $\text{NH}_4^+$  to  $\text{NH}_3$ . The linear  $\text{NH}_4^+$  partition coefficient of soil gives the  $\text{NH}_4^+$  binding capacity of the soil. The more  $\text{NH}_4^+$  binds (adsorbs) to the soil, the less  $\text{NH}_3$  will be available for volatilization from the soil surface.

## **4. RESULTS AND DISCUSSION**

Results of the ammonia emission study are presented and discussed. Seasonal lagoon effluent PAN coefficients based on  $\text{NH}_3$  emission and org-N mineralization rate are presented for the traveling gun and drag hose systems. Measured and modeled  $\text{NH}_3$  emissions are presented and discussed. Finally, results of the sensitivity analyses for four parameters are presented and discussed.

### **4.1. Ammonia Emission**

Ammonia emission during 0-4 h, 4-24 h and subsequent 24 h periods are presented and discussed. The emissions for traveling gun and drag hose are presented separately.

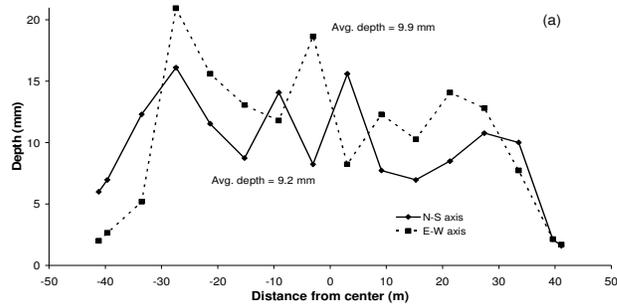
#### **4.1.1. Traveling gun**

Ammonia concentrations and emissions from the traveling gun during and after application are presented and discussed. The first two periods (0-4 h and 4-24 h), when emissions were higher, are discussed in greater detail than the subsequent 24 h periods.

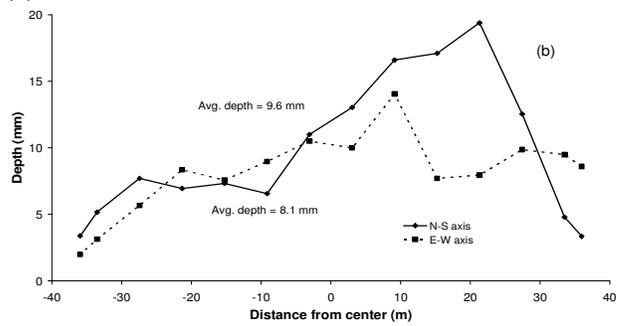
##### **A. Drift and evaporation**

Figure 4.1 shows the depths of effluent in the catch cans in N-S and E-W transects. The wetted diameters were measured during land application as described in Materials and Methods. The catch can depths outside the diameter were added evenly to catch cans inside. The average depth had two sources of uncertainty. The wetted diameter of the traveling gun

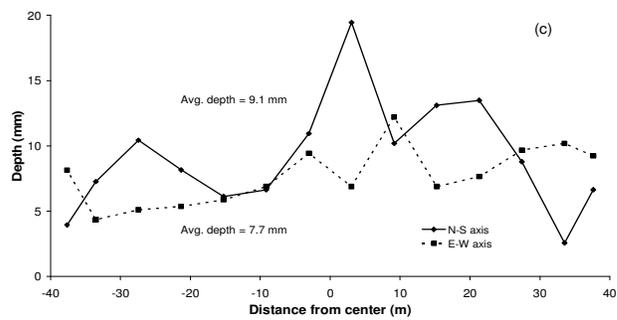
plot was averaged only four times while the gun likely made >25 passes (based on 2 min rotation time). The other source of uncertainty was the variable wind speed and direction. Wind effects were the most pronounced during the May 2006 application period when collection was much higher at the north vs. the south end (Fig. 4.1(b)).



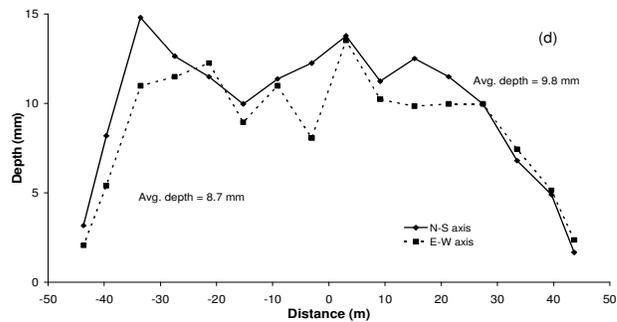
(a) October 2005



(b) May 2006



(c) June 2006



(d) July 2006

**Figure 4.1. Depths of effluent in catch cans in the (a) October 2005, (b) May 2006, (c) June 2006 and (d) July 2006 monitoring periods.**

Table 4.1 summarizes the drift and evaporation calculated during the application; application depths are also listed. Chloride concentrations in the catch cans vs. the nozzle were used to estimate evaporation (Table 4.1).

**Table 4.1. Application depths, chloride (Cl) concentration in nozzle and catch cans, and evaporation and drift losses.**

Parameter	Oct 2005	May 2006	June 2006	July 2006
Flowmeter depth (mm)	11.2	10.8	8.5	10.1
Flowmeter depth (mm)	11.7	10.9	8.5	10.5
Catch can depth (mm) <sup>1</sup>	9.6 (4.9)	8.9 (4.3)	8.4 (3.5)	9.2 (3.3)
Cl in nozzle (mg/L) <sup>2</sup>	550 (5)	625 (21)	638 (5)	656 (7)
Cl in catch can (mg/L) <sup>3</sup>	628 (23)	724 (39)	705 (47)	777 (27)
Evaporation (%) <sup>4</sup>	12.4	11.9	9.5	15.6
Drift (%) <sup>5</sup>	1.9	5.7	-8.2	-6.7

<sup>1</sup>Average of 28 catch cans and standard deviation

<sup>2</sup>Average of 4 samples

<sup>3</sup>Average of 14 samples

<sup>4</sup>Refer Eq. [3.10]

<sup>5</sup>Refer Eq. [3.11]

Evaporation of effluent droplets between the nozzle and the soil surface ranged from 9.5 to 15.6%. In this study, evaporation losses were generally higher than those reported in the literature. McLean et al. (2000) reported evaporation loss ~8% based on the difference in electrical conductivity of liquid in nozzle vs. catch cans. The effluent temperature in this study was considerably higher than 7-8° C groundwater temperature used in McLean study (McLean et al., 2000); hence, higher evaporation would be expected in this study. In July 2006, the average air temperature and relative humidity were 32° C and 42%; such conditions

were conducive to high evaporation losses from a traveling gun with a ring nozzle as was used in this study.

Drift ranged from -8.2 to 5.7%; this was likely due to changing wind speed and direction. The negative drift values during June and July 2006 indicated the uncertainties in the calculation of evaporation and depth collected in the catch cans. The calculation of drift and evaporation were not the main objective of the study, hence, this matter was not pursued further.

#### B. Ammonia-N loss during application

The results of  $\text{NH}_3\text{-N}$  loss during application are presented in Table 4.2. The  $\text{NH}_3\text{-N}$  loss was from the nozzle of the gun to the catch can. The IHF method calculates the emissions from the soil surface according to the concentration boundary layer profile. The  $\text{NH}_3$  emission in the trajectory would not be captured in the lower (0.2 and 0.6 m height) scrubbers. During 0-4 h monitoring period,  $\text{NH}_3$  concentrations of lower heights were used (refer to Materials and Methods). Thus, the emissions from IHF method would not include the  $\text{NH}_3\text{N}$  loss during application. Hence, it would be appropriate to add the emissions presented in Table 4.2 to obtain total  $\text{NH}_3\text{N}$  loss. The  $\text{NH}_3\text{N}$  loss ranged 3.8 to 10.7% of applied TAN. Sharpe and Harper (2002) reported  $\text{NH}_3$  emission of 12% of the applied-N during application based on TAN concentration difference. Al-Kaisi and Waskom (2002) reported that  $\text{NH}_3$  emission ranged from 8 to 27% of applied-TAN. The  $\text{NH}_3$  losses in this study are comparable to those reported by Sharpe and Harper (2002) and are at the lower end of the range of values reported by Al-Kaisi and Waskom (2002). The major source of

uncertainty for determining NH<sub>3</sub>-N loss during application was the uncertainty associated with calculating drift and evaporation.

**Table 4.2. Ammoniacal nitrogen (TAN) concentrations in the traveling gun nozzle and catch can samples and ammonia loss during application.**

Parameter	October 2005	May 2006	June 2006	July 2006
TAN in nozzle <sup>1</sup>	421 (8)	726 (40)	712 (7)	562 (3)
TAN in catch can <sup>2</sup>	455 (9)	787 (30)	693 (52)	570 (16)
NH <sub>3</sub> -N loss, % of applied TAN <sup>3</sup>	7.4	10.7	3.8	7.6
pH in nozzle <sup>1</sup>	7.81 (0.09)	7.79 (0.06)	7.98 (0.04)	7.64 (0.03)
pH in catch cans <sup>2</sup>	7.95 (0.16)	N/M <sup>4</sup>	7.85 (0.07)	8.39 (0.13)

<sup>1</sup> Average (standard deviation) of 4 samples

<sup>2</sup> Average (standard deviation) of 14 samples

<sup>3</sup> Refer Eq. [3.12]

<sup>4</sup> Not measured

The loss of NH<sub>3</sub> would result in decrease in pH of the effluent (Table 4.2). However the increase in pH during observed in October 2005 and July 2006 (Table 4.2) could be due to loss of CO<sub>2</sub> from the effluent. However, it may be noted that the catch can pH values were not adjusted for loss in volume.

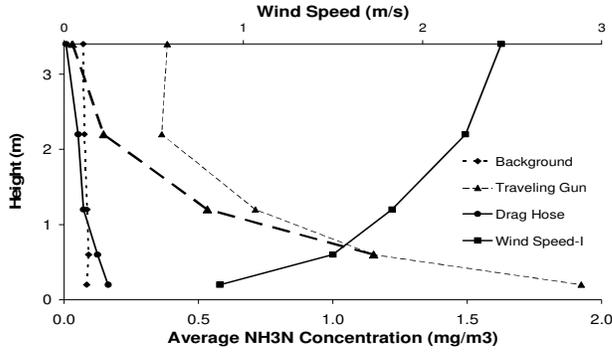
### C. 0-4 h

#### Ammonia concentration

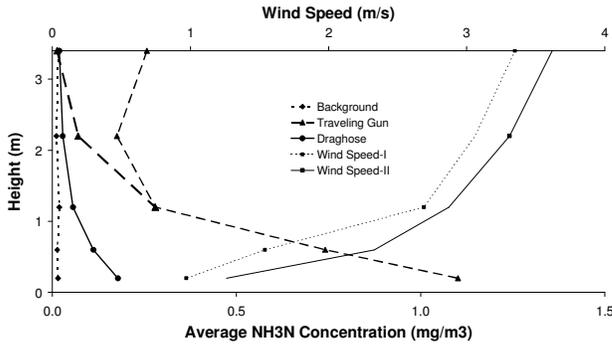
Ammonia concentration profiles in the traveling gun plot and background masts, and wind speed profiles during 0-4 h period are presented in Fig. 4.2. For October 2005, June and July 2006, measured NH<sub>3</sub>N concentrations at 0.2-m and 0.6-m heights were extrapolated

using a logarithmic trendline to estimate  $\text{NH}_3\text{N}$  concentrations at 1.2-m, 2.2-m and 3.4-m heights (Fig. 4.2). For May 2006, the measured  $\text{NH}_3\text{N}$  concentration at 1.2 m was also used for the trendline to estimate  $\text{NH}_3\text{N}$  concentrations at 2.2-m and 3.4-m.

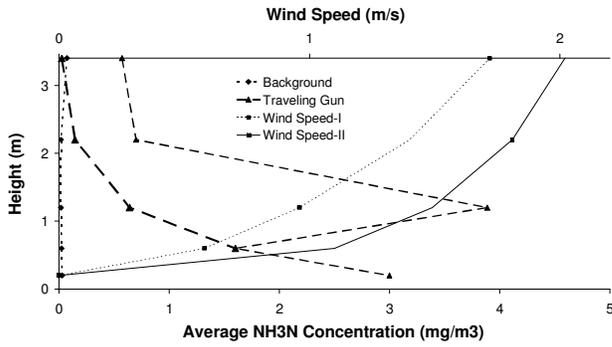
**Figure 4.2. Ammonia concentration profiles in 0-4 h monitoring periods in the traveling gun, drag hose, and background masts for (a) October 2005, (b) May 2006, (c) June 2006 and (d) July 2006. The dark dashed line extending from the traveling gun  $\text{NH}_3\text{N}$  concentration is the extrapolated log profile from lower  $\text{NH}_3\text{N}$  concentrations. Wind speed profiles by both method-I and II are also plotted (indicated in the plot as wind speed-I and wind speed-II). The actual  $\text{NH}_3\text{N}$  concentration data for the 3.4-m height for the traveling gun in July 2006 was lost.**



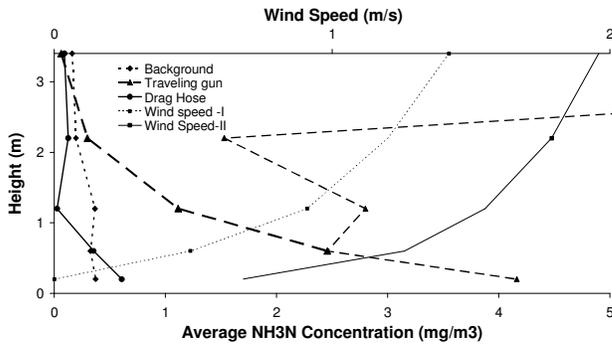
(a) October 2005



(b) May 2006



(c) June 2006



(d) July 2006

The upper limit of the zone of profile development ( $z_p$ ), obtained from extrapolation of  $\text{NH}_3\text{N}$  concentrations to background concentrations, were 2.03, 1.88, 1.67, and 1.95 m for October 2005, May, June, and July 2006, respectively. Hence, use of a total sampling height of 4.0 m ( $3.4+\Delta z_5/2$ ) was adequate to capture  $\text{NH}_3$  within the  $z_p$ .

#### Ammonia emission (IHF method)

The  $\text{NH}_3\text{-N}$  emission results are presented in Table 4.3. The emissions calculated using wind speed calculated by method-I ranged from 6.9 to 21.5% of applied-TAN. Using method-II, emissions ranged from 11.5 to 19.3% of applied-TAN. The emission values obtained from method-II were used in PAN calculation (for October 2005, only method-I could be used) because the logarithmic profile calculated with continuous wind speed measured at 2.2-m height better represented the transport phenomenon than 10-min values at four heights.

**Table 4.3. Weather parameters and ammonia emission calculated with the IHF method using two different methods of wind speed calculation<sup>1</sup>.**

Monitoring period	Temp, RH, Wind	Traveling gun emission		Drag hose emission	
	speed at 2.2 m height (C, %, m/s)	kg/ha	% loss <sup>3</sup>	kg/ha	% loss <sup>3</sup>
<b>October 2005<sup>2</sup></b>					
0-4 h	19.8, 35, 2.0	9.47 <sup>4,5</sup>	21.5 <sup>4</sup>	0.04	0.1
4-24 h	12.2, 74, 0.6	1.94	4.4	0.16	0.3
24-48 h	18.5, 68, 0.7	0.22	0.5	0.05	0.1
48-72 h	20.9, 69, 0.8	0.03	0.1	0.04	0.1
72-96 h	21.3, 75, 0.8	0.26	0.6	0.15	0.3
96-120 h	22.1, 78, 1.1	0.13	0.3	0.02	0.0

Table 4.3 (continued).

<b>Total</b>		<b>12.05</b>		<b>27.4</b>		<b>0.46</b>		<b>0.9</b>	
<b>May 2006</b>									
		<b>Method-I</b>		<b>Method-II</b>		<b>Method-I</b>		<b>Method-II</b>	
		<b>%</b>		<b>%</b>		<b>%</b>		<b>%</b>	
		<b>kg/ha</b>	<b>loss</b>	<b>kg/ha</b>	<b>loss</b>	<b>kg/ha</b>	<b>loss</b>	<b>kg/ha</b>	<b>loss</b>
0-4 h	23.9, 48, 3.2	7.08	9.1	9.02	11.5	2.27	2.9	2.76	3.5
4-24 h	15.4, 81, 1.2	1.49	1.9	2.42	3.1	0.25	0.3	0.62	0.8
24-48 h	15.5, 71, 1.2	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
48-72 h	17.5, 65, 2.4	0.14	0.2	0.31	0.4	0.15	0.2	0.31	0.4
72-96 h	18.6, 68, 2.3	0.09	0.1	0.17	0.2	0.34	0.4	0.47	0.6
<b>Total</b>		<b>8.80</b>	<b>11.3</b>	<b>11.92</b>	<b>15.2</b>	<b>3.01</b>	<b>3.8</b>	<b>4.16</b>	<b>5.3</b>
<b>June 2006</b>									
0-4 h	29.3, 59, 1.7	4.40	7.3	7.13	11.8				
4-24 h	19.7, 95, 1.8	0.10	0.2	0.45	0.7				
24-48 h	20.7, 97, 4.0	1.23	1.7	1.05	2.0				
<b>Total</b>		<b>5.73</b>	<b>9.2</b>	<b>8.63</b>	<b>14.5</b>				
<b>July 2006</b>									
0-4 h	32.6, 39, 1.8	3.93	6.9	11.00	19.3	0.03	0.0	0.46	0.7
4-24 h	26.9, 72, 0.6	0.57	1.0	3.14	5.5	0.24	0.3	0.96	1.4
24-48 h	27.9, 70, 0.9	0.98 <sup>4</sup>	1.7 <sup>4</sup>	2.57 <sup>4</sup>	4.5 <sup>4</sup>	0.38	0.6	1.05	1.5
48-72 h	27.5, 67, 1.4	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
72-96 h	23.7, 86, 1.4	0.08	0.1	0.14	0.2	0.00	0.0	0.00	0.0
<b>Total</b>		<b>5.56</b>	<b>9.7</b>	<b>16.85</b>	<b>29.5</b>	<b>0.65</b>	<b>0.9</b>	<b>2.47</b>	<b>3.6</b>

<sup>1</sup> Method-I used 10-min wind speed values for 0.2, 0.6, 1.2, and 3.4 m (not in July 2006) and interpolated value of wind speed at 2.2-m height to develop profile. Method-II used the 10-min average wind speed values at 2.2-m height to calculate wind speeds at the other heights using the logarithmic profile

<sup>2</sup> Calculated using Method-I

<sup>3</sup> Percent of applied TAN lost

<sup>4</sup> NOT corrected for background emission (based on wind direction)

<sup>5</sup> For the 0-4 h period, emissions from the traveling gun were always calculated based on a theoretical logarithmic concentration profile developed by extrapolating the measured ammonia concentrations at 0.2, and 0.6 m heights, and in May 2006, also the 1.2 m height.

Ammonia emissions depend on weather parameters (seasonal effects) like relative humidity and temperature. In July 2006, RH was low and temperatures were high resulting in high  $\text{NH}_3$  emissions. The use of  $\text{NH}_3$  concentrations in lower sampling heights meant  $\text{NH}_3$  losses during the land application would not be included in 0-4 h  $\text{NH}_3$  emissions.

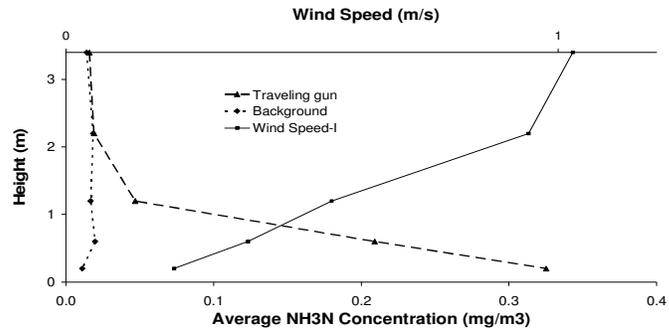
Based on the wind rose diagrams the background concentrations were not deducted in October 2005 from traveling gun mast. The wind was blowing from traveling gun plot to the background mast during this period (Fig. 3.9). The background concentrations were deducted from drag hose mast as the traveling gun emissions probably affected both the drag hose mast and background mast. However, this approach might have led to underestimation of  $\text{NH}_3\text{N}$  emission from drag hose plot.

D. 4-24 h

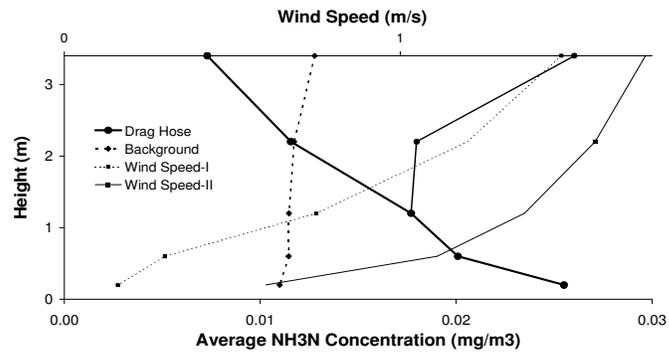
#### Ammonia concentration

Ammonia concentration profiles in the traveling gun plot and background masts, and wind speed profiles during 4-24 h period are presented in Fig. 4.4. The concentration data for the traveling gun for May 2006 was not available. The concentration profiles for October 2005, June and July 2006 were more-or-less logarithmic (Fig 4.4 (a), (c), (d)). The profiles for 4-24 h period reinforced the concept of log concentration profiles from the treated plots by Harper et al. (1983).

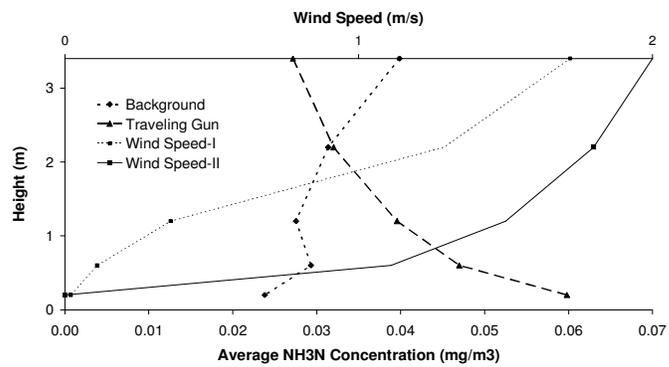
**Figure 4.5. Ammonia concentration profiles in 4-24 h monitoring periods. Wind profiles using both method-I and method-II are also shown.**



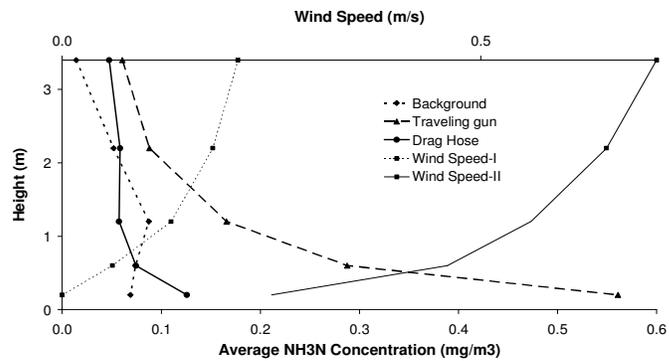
(a) October 2005



(b) May 2006



(c) June 2006



(d) July 2006

The  $\text{NH}_3$  concentration profile for the drag hose in May 2006 was unexpected; the concentrations increased above the 1.2-m height. The wind rose diagram indicated minimal impact of the traveling gun plot; and the background concentrations did not vary with height. Hence, for the 4-24 h period in May 2006,  $\text{NH}_3$  emission from the plot was calculated by obtaining corrected concentrations for 2.2 and 3.4 m heights by forcing a log profile through the  $\text{NH}_3$  concentrations of lower heights (Fig. 4.4(b)).

#### Ammonia emission

Ammonia emissions from the traveling gun plot during 4-24 h are presented in Table 4.3. The emissions using method-II of wind speed calculations were 0.7 and 5.5% of applied-TAN in June and July 2006, respectively; higher emissions in July were attributed to warmer and drier (low RH) conditions. Using method-I emissions were 4.4, 0.2 and 1.0% of applied-TAN in October 2005, June and July 2006. For May 2006, the estimated emissions during 4-24 h were obtained by averaging % of applied TAN losses in June and July 2006 using method-II. Similarly, the May emission using method-I, 1.9% of applied TAN, was obtained by averaging October 2005, June and July 2006  $\text{NH}_3\text{N}$  emissions. The emissions during this period were < 6%; hence, the uncertainty due to estimation of May 2006  $\text{NH}_3\text{N}$  emission would not affect the PAN calculation to a great extent.

#### Subsequent 24 h periods

Subsequent  $\text{NH}_3\text{N}$  emissions, calculated every 24 h are also presented in Table 4.3. Since the emissions during these periods were very low (vs. emissions during the first 24 h), the

concentration and wind speed profiles (from both methods) are not presented. The background  $\text{NH}_3\text{N}$  concentrations were deducted for all periods.

#### **4.1.2. Drag hose**

##### **A. 0-4 h**

Average ammonia concentrations during 0-4 h in drag hose plot are presented in Fig. 4.2. Using method-I, ammonia emissions were 0.7, 2.9 and 0.3% of applied-TAN in October 2005, May and July 2006 respectively. The emissions by method-II were 3.5 and 0.7% of applied-TAN in May and July 2006. The actual  $\text{NH}_3\text{N}$  emissions during this period may have been slightly higher than the measured values as air sampling started after application had been completed. As with the traveling gun, emissions calculated using method-II were considered more representative of the transport phenomenon.

##### **B. 4-24 h**

Average  $\text{NH}_3$  concentrations and wind speed profiles during 4-24 h periods are presented in Fig. 4.4. Using method-I, loss of N due to  $\text{NH}_3$  emissions were 2.5 % and 0.1% of applied-TAN in July and May. Using method-II the  $\text{NH}_3$  emissions were 3.0 and 1.4% of applied-TAN in May and July 2006

##### **C. Subsequent 24 h periods**

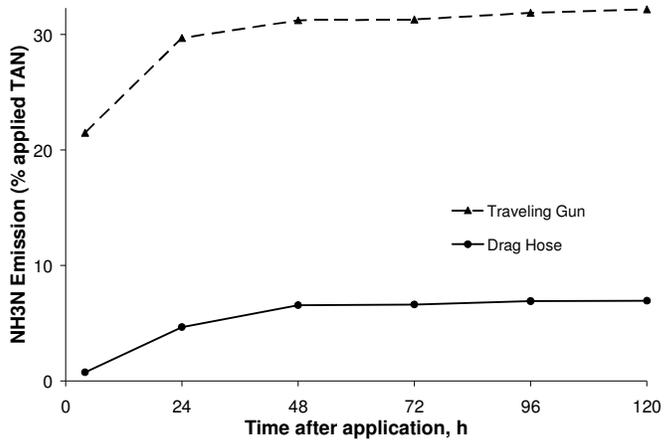
The subsequent 24 h  $\text{NH}_3\text{N}$  emissions are presented in Table 4.3. The emissions were low and comparable to emissions from traveling gun treated plots of the same application period.

It suggests that 24 h after application the  $\text{NH}_3\text{N}$  emissions does not depend on method of application.

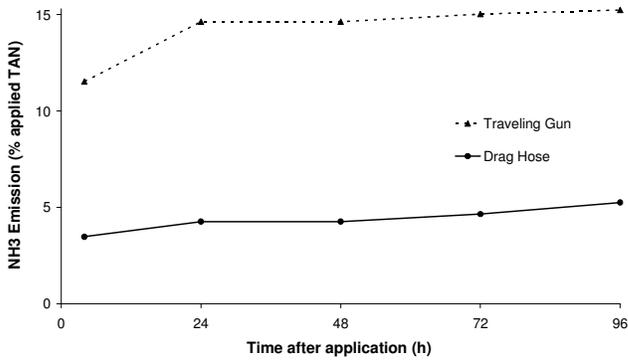
#### **4.1.3. Ammonia emissions from the traveling gun and drag hose systems**

Land application of hog anaerobic effluent with traveling gun resulted in 3 to 30 times more % TAN loss as  $\text{NH}_3$  emission than with drag hose. The higher losses could be attributed to 3.8 to 10.7% loss of TAN during application by traveling gun; with the drag hose, this loss was likely negligible. Another reason for the low loss was that the soil was aerated during the application with the drag hose, so the effluent infiltrated the soil more rapidly. After the first 24 h of application, it seemed that ammonia emissions were lower (than the first 24 h) and comparable for both treatments (Fig. 4.5).

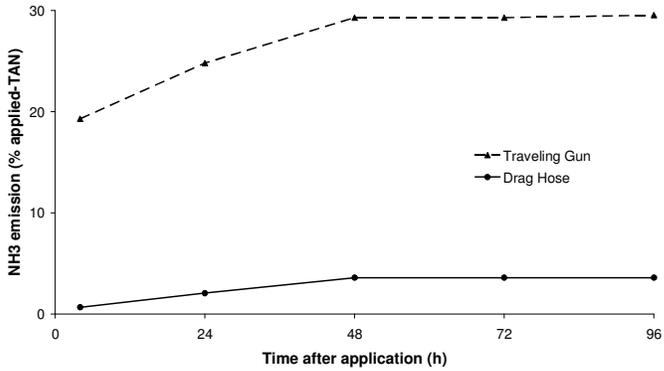
Figure 4.5 compares  $\text{NH}_3$  emissions from the two treatments, as % of applied-TAN, during Oct 2005, May and July 2006 monitoring periods. Sullivan et al. (2003) reported  $\text{NH}_3$  emission of 8 to 31% applied-N from the traveling gun. Sharpe and Harper (2002) calculated  $\text{NH}_3$  emissions of 35% of applied-N, including 12% during application. Since the  $\text{NH}_3$  emissions from the traveling gun in this study ranged from 13 to 26% of total N (or TKN) applied (note that Fig. 4.5 reports in % of applied TAN), the findings of study are in line with findings reported in published literature. No studies on  $\text{NH}_3$  emissions from the drag hose system could be located.



(a) October 2005



(b) May 2006



(c) July 2006

**Figure 4.5. Comparison of cumulative ammonia emissions from the traveling gun and drag hose plots.**

## 4.2. Calculation of PAN Coefficients

The PAN coefficients are presented in Table 4.4 for the traveling gun and drag hose systems for each application period accounting for calculated NH<sub>3</sub>-N emissions and published N-mineralization fractions. Please note that the NH<sub>3</sub>-N emissions in Table 4.3 are expressed as % applied TAN; those values were converted to % applied N by multiplying with respective TAN to TKN ratio. It should also be noted that PAN coefficients includes NH<sub>3</sub> losses measured with the catch cans. While the possibility of slight underestimation of the PAN coefficient with this approach cannot be ruled out, neglecting the losses may introduce more errors. The calculated mean PAN coefficients, thus obtained, are 0.67 and 0.88 for hog lagoon effluent applied with traveling gun and drag hose, respectively. While the PAN coefficient for the traveling gun varied substantially among the four period, the PAN for the drag hose was unaffected by the environmental conditions.

**Table 4.4. PAN coefficients for traveling gun and drag hose, and weather conditions during the first 4 h beginning effluent application.**

Application period	Environmental conditions during the 0-4 h period			PAN coefficient	
	Mean Temp. (C)	Mean RH (%)	Mean wind speed @ 2.2 m height (m/s)	Traveling Gun	Drag Hose
	Oct. 2005 <sup>1</sup>	19.8	35	2.2	0.60
May 2006	23.9	48	3.2	0.69	0.88
June 2006	29.3	59	1.8	0.78 <sup>2</sup>	N/A <sup>3</sup>
July 2006	32.2	42	1.8	0.60	0.89
<b>Mean</b>	<b>26.3</b>	<b>46</b>	<b>2.2</b>	<b>0.67</b>	<b>0.88</b>

<sup>1</sup>Greater uncertainty in wind speed measurement (method-I used)

<sup>2</sup>Based on only 48 h NH<sub>3</sub> emission data

<sup>3</sup>Not applied

For land application, by both, the traveling gun and drag hose systems, based on the finding of the current study, the current PAN coefficient of 0.50 could result in over application of N. However, it is recognized that uncertainties in this study (primarily, use of the extrapolated logarithmic wind profile and ammonia concentration profile for the traveling gun during the 0-4 h) may have affected the results.

### **4.3. Modeling Ammonia Emissions**

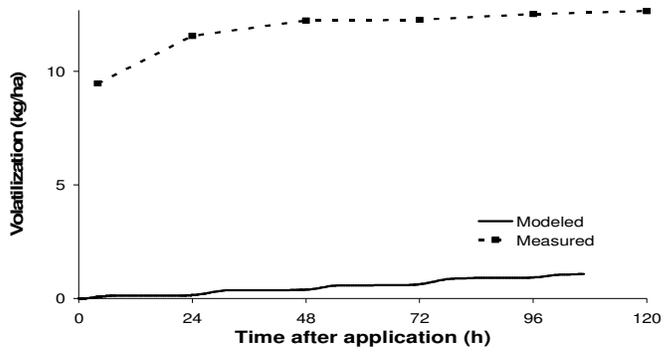
Modeled and measured NH<sub>3</sub> emissions following land applications of lagoon effluent using the traveling gun and drag hose systems are compared. Sensitivity analyses of the model for four parameters are also presented and discussed. The input files used for the modeling are presented in Appendix A and the command prompt output screen showing the mass balance of water and ammoniacal N are presented in Appendix B.

#### **4.3.1. Comparisons of modeled and measured emissions**

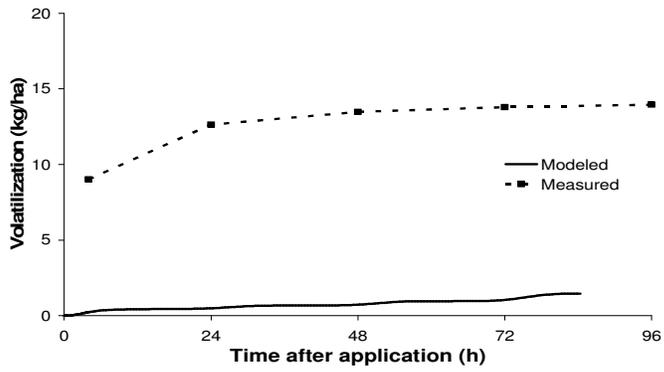
The model by Wu et al. (2003a) had been validated in the field by Warren (2001) and Zupancic (1999). In both field studies, swine effluent had been applied to bare soil by flood irrigation. In this study the soil was covered with 76-300 mm of Coastal Bermudagrass and the land application was done using both, a traveling gun (sprinkler irrigation) and drag hose. The model (Wu et al., 2003a) had the capability to simulate both sprinkler irrigation and flood irrigation but it had not been validated for sprinkler application. It was also recognized that the flood irrigation as simulated by the model was slightly different than application of effluent using the drag hose.

Figure 4.6 compares the modeled (Wu et al., 2003a) NH<sub>3</sub> emissions with the measured emissions from the traveling gun. The modeled NH<sub>3</sub> emissions were lower than the measured values by 91.4, 89.5, 65.7 and 38.8% in October 2005, May, June and July 2006, respectively. Close inspection of the results revealed that the slopes of the modeled and measured emissions 4 h following effluent application were similar in all four application periods. Hence, the model underestimations were mainly during the first 4 h.

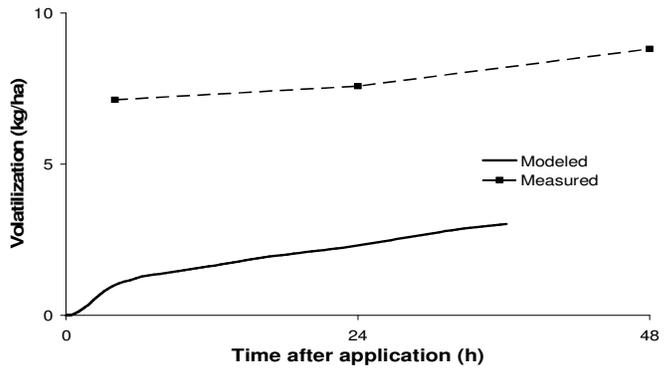
**Figure 4.6. Comparison of measured and modeled ammonia emissions from the traveling gun plot.**



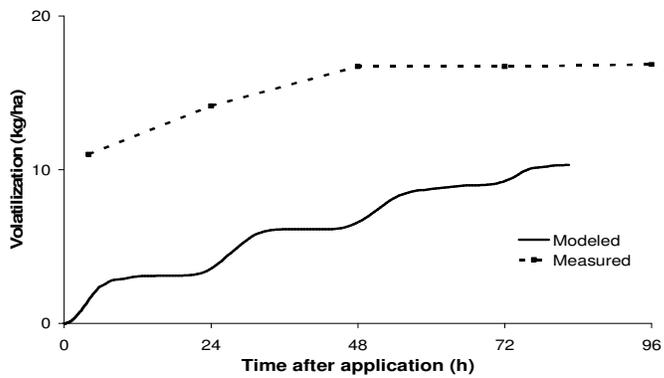
(a) October 2005



(b) May 2006



(c) June 2006

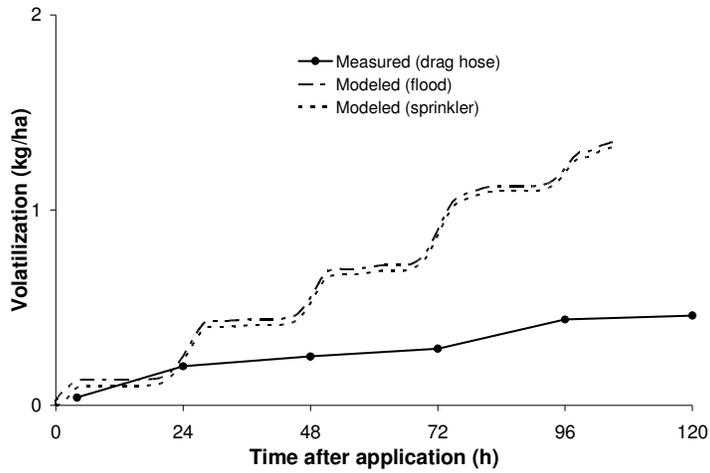


(d) July 2006

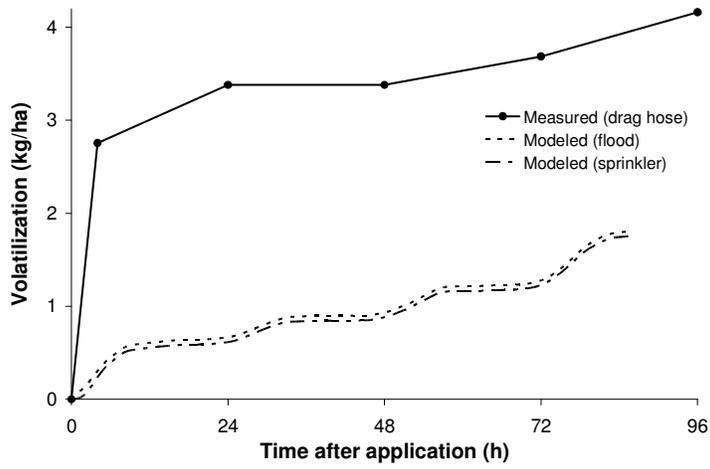
It seemed that the model did not sufficiently simulate the canopy interception of effluent, subsequent drying, and  $\text{NH}_3$  emissions. The traveling gun made several passes to apply the effluent on the land. Only a fraction of effluent was applied in one pass, which could have led to greater evaporation of the intercepted effluent from the canopy and also the soil (between passes) and hence, greater  $\text{NH}_3$  volatilization than if all the effluent had been applied.

Figure 4.7 compares the modeled (Wu et al., 2003a)  $\text{NH}_3$  emissions model, using both sprinkler and flood irrigation model, with the measured emissions from drag hose plot. The measured  $\text{NH}_3$  emissions from field were 66 and 78% lower than the simulated emissions during October 2005 and July 2006 (Fig. 4.7). However, in May 2006, the simulated emissions were lower than the measured emission by 58%. In May 2006, wind speeds during the 0-4 h period were considerably higher than other periods which caused measured  $\text{NH}_3$  emissions from treated plot to be higher than other periods. However the model did not seem to respond to the higher wind speed values during May 2006 and showed a profile that was similar to the October 2005 and July 2006 profiles, resulting in lower simulated emissions. Another reason for the inability of the model to simulate effluent application by the drag hose unit was its inability to account for aeration that substantially reduced the measured emissions.

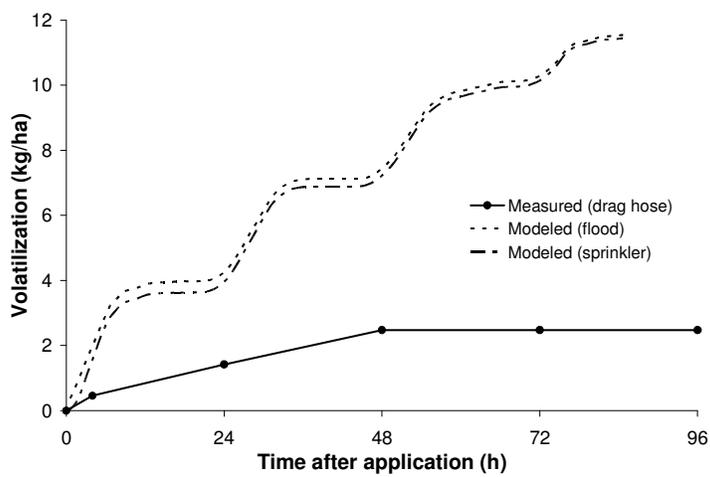
**Figure 4.7. Comparison of measured and modeled ammonia emissions from the drag hose plot.**



(a) October 2005



(b) May 2006



(c) July 2006

The simulated emissions from flood and sprinkler irrigation were nearly identical (Fig. 4.7). Hence, it seemed that the model did not sufficiently distinguish between the two application methods. Following the earlier discussion on sprinkler irrigation, one would expect to see more NH<sub>3</sub> emission from sprinkler. Perhaps this fact explains the lower emissions predicted by the model with traveling gun application.

Also, the modeled soil temperatures were less than the measured values by 3-4°C. The difference in temperatures, in part, might explain the lower cumulative emissions. Further, the model was not sensitive to change in effluent pH. Higher effluent pH should have resulted in higher NH<sub>3</sub> emissions. This would also partly explain the discrepancy between the model and measured values.

#### 4.3.2. Sensitivity analysis

Table 4.5 gives the details of the sensitivity analyses performed on the model. The following four parameters were chosen for the analysis: (1) TAN concentration, (2) soil pH, (3) linear NH<sub>4</sub><sup>+</sup> partition coefficient of soil, (4) wind speed at 2 m height.

**Table 4.5. Sensitivity analysis of Wu et al. (2003a) model for the July 2006 monitoring period.**

Parameter	Baseline	Baseline	Output	Sr	Sensitivity
	Value	change (%)	change (%)		
TAN Conc (g/L)	0.562	20	19.2	0.96	moderately sensitive
		-20	-19.9	0.99	moderately sensitive
Linear Partition Coefficient (mL/g)	2.58	75	-16.5	-0.22	moderately sensitive
		-75	32.5	-0.43	moderately sensitive

Table 4.5 (continued).

Soil pH	6.7	50	67.7	1.35	sensitive
		-50	-29.6	0.59	moderately sensitive
Wind Speed		50	29.1	0.58	moderately sensitive
		-50	-37.8	0.76	moderately sensitive

The model was moderately sensitive to an increase in TAN concentration of effluent and sensitive to a decrease in TAN from baseline values. The model was moderately sensitive to decrease in soil pH and sensitive to increase in soil pH as the fraction of  $\text{NH}_3$  in solution increases with pH. The model was moderately sensitive to the soil-solution partition coefficient and wind speed. A higher partition coefficient increases the fraction of  $\text{NH}_4^+$  adsorbed to the soil particles which would lower the  $\text{NH}_4^+$  available for dissociation to  $\text{NH}_3$  resulting in lower  $\text{NH}_3$  emissions. A higher wind speed would result in more convective transfer of  $\text{NH}_3$  increasing the concentration gradient resulting in more emissions.

## 5. CONCLUSIONS AND FUTURE RESEARCH

Ammonia-N emission during land application with the traveling gun, ranged from 3 to 9% of applied-N. The cumulative N loss due to NH<sub>3</sub> emissions, 96 h after the start of application ranged from 13 to 26% of applied-N, with very high (65 to 81%) of emission taking place in first 4 h. The N loss during the application (trajectory of effluent) ranged from 4 to 11%. The cumulative NH<sub>3</sub> emission, for land application using the drag hose, ranged from 1 to 5%. Based on literature, N-mineralization rate during the crop growing season was assumed to be 50%. The PAN (fraction of total N), thus obtained, was 0.65 for traveling gun, and 0.85 for drag hose. A model was used to simulate NH<sub>3</sub> emission from hog lagoon effluent using the traveling gun. The model underestimated NH<sub>3</sub> emission from the plots applied with traveling gun, especially in the first 4 h. The model over predicted the NH<sub>3</sub> emission in two of the three applications with the drag hose. The model was sensitive to increase in soil pH and moderately sensitive to changes in all other selected parameters (ammoniacal-N concentration and pH of effluent, linear partition coefficient of soil, and wind speed).

Based on the results of this study, the following future research recommendations are:

- More NH<sub>3</sub> emission data under various weather condition and different types of soil following land application of hog anaerobic lagoon effluent.
- Less sampling intervals for NH<sub>3</sub> concentrations following land application to better understand the mechanism of NH<sub>3</sub> volatilization.

- Due to uncertainties in the  $\text{NH}_3$  emission measurement with the traveling gun, additional studies are needed with improved methods to account for losses in the mist during application.
- Improvement of  $\text{NH}_3$  emission model (Wu et al., 2003a) to better simulate traveling gun application on soil with canopy cover.

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**APPENDIX A. INPUT FILES USED IN MODELING**  
**AMMONIA EMISSION**

## October 2005

### A. Traveling gun

Max Time 120.0  
Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
Depth Applied 1.12 cm  
Total Ammoniacal N Concentration 0.421 in g L-1  
Manure pH 7.81  
Soil pH 6.7  
Dispersivity 0.4 cm  
Partition Coefficient 2.58 cm<sup>3</sup> g-1  
van Genuchten alpha 0.0135 cm-1  
van Genuchten n 1.3830  
Saturated Water Content 0.4553  
Residual Water Content 0.0834  
Saturated Hydraulic Conductivity 8.37 cm hr-1  
Sand Particle 93.3 mass percentage  
Clay Particle 3.6 mass percentage  
Field Width in Wind Direction 41.15 in m  
Start Time 10.5 hour of a day  
Water Flow Iteration Criterion 1.0E-5 in %  
Mass Balance Criterion for Water 5.0 in %  
Weather Data HourlyWeatherOct.txt  
Output Process Oct.txt  
Canopy Height 0.0 in cm

### B. Drag hose using sprinkler module

Max Time 120.0  
Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
Depth Applied 1.24 cm  
Total Ammoniacal N Concentration 0.421 in g L-1  
Manure pH 7.65  
Soil pH 6.7  
Dispersivity 0.4 cm  
Partition Coefficient 2.58 cm<sup>3</sup> g-1  
van Genuchten alpha 0.0135 cm-1  
van Genuchten n 1.3830  
Saturated Water Content 0.4553  
Residual Water Content 0.0834  
Saturated Hydraulic Conductivity 8.37 cm hr-1  
Sand Particle 93.3 mass percentage  
Clay Particle 3.6 mass percentage  
Field Width in Wind Direction 18.76 in m  
Start Time 13.3 hour of a day  
Water Flow Iteration Criterion 1.0E-5 in %  
Mass Balance Criterion for Water 5.0 in %  
Weather Data HourlyWeatherOct.txt  
Output Process OctDH.txt  
Canopy Height 0.0 in cm

### C. Drag hose using flood irrigation

Max Time 120.0  
Irrigation Type 1 0---Sprinkler irrigation; 1---Flood irrigation  
Depth Applied 1.24 cm  
Total Ammoniacal N Concentration 0.421 in g L-1  
Manure pH 7.65  
Soil pH 6.7  
Dispersivity 0.4 cm  
Partition Coefficient 2.58 cm<sup>3</sup> g-1  
van Genuchten alpha 0.0135 cm-1  
van Genuchten n 1.3830  
Saturated Water Content 0.4553  
Residual Water Content 0.0834  
Saturated Hydraulic Conductivity 8.37 cm hr-1  
Sand Particle 93.3 mass percentage  
Clay Particle 3.6 mass percentage  
Field Width in Wind Direction 18.76 in m  
Start Time 13.3 hour of a day  
Water Flow Iteration Criterion 1.0E-5 in %  
Mass Balance Criterion for Water 5.0 in %  
Weather Data HourlyWeatherOct.txt  
Output Process OctDH1.txt  
Canopy Height 0.0 in cm

### May 2006

#### A. Traveling gun

Max Time 96.0  
Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
Depth Applied 1.08 cm  
Total Ammoniacal N Concentration 0.726 in g L-1  
Manure pH 7.8  
Soil pH 6.5  
Dispersivity 0.4 cm  
Partition Coefficient 2.58 cm<sup>3</sup> g-1  
van Genuchten alpha 0.0135 cm-1  
van Genuchten n 1.3830  
Saturated Water Content 0.4553  
Residual Water Content 0.0834  
Saturated Hydraulic Conductivity 8.37 cm hr-1  
Sand Particle 93.26 mass percentage  
Clay Particle 3.64 mass percentage  
Field Width in Wind Direction 35.96 in m  
Start Time 11.92 hour of a day  
Water Flow Iteration Criterion 1.0E-5 in %  
Mass Balance Criterion for Water 5.0 in %  
Weather Data HourlyWeatherMay.txt  
Output Process May.txt  
Canopy Height 0.0 in cm

### B. Drag hose using sprinkler irrigation module

Max Time 96.0  
Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
Depth Applied 1.04 cm  
Total Ammoniacal N Concentration 0.760 in g L-1  
Manure pH 7.7  
Soil pH 6.5  
Dispersivity 0.4 cm  
Partition Coefficient 2.58 cm<sup>3</sup> g-1  
van Genuchten alpha 0.0135 cm-1  
van Genuchten n 1.3830  
Saturated Water Content 0.4553  
Residual Water Content 0.0834  
Saturated Hydraulic Conductivity 8.37 cm hr-1  
Sand Particle 93.26 mass percentage  
Clay Particle 3.64 mass percentage  
Field Width in Wind Direction 16.81 in m  
Start Time 11.92 hour of a day  
Water Flow Iteration Criterion 1.0E-5 in %  
Mass Balance Criterion for Water 5.0 in %  
Weather Data HourlyWeatherMay.txt  
Output Process MayDH.txt  
Canopy Height 0.0 in cm

### C. Drag hose using flood irrigation module

Max Time 96.0  
Irrigation Type 1 0---Sprinkler irrigation; 1---Flood irrigation  
Depth Applied 1.04 cm  
Total Ammoniacal N Concentration 0.760 in g L-1  
Manure pH 7.7  
Soil pH 6.5  
Dispersivity 0.4 cm  
Partition Coefficient 2.58 cm<sup>3</sup> g-1  
van Genuchten alpha 0.0135 cm-1  
van Genuchten n 1.3830  
Saturated Water Content 0.4553  
Residual Water Content 0.0834  
Saturated Hydraulic Conductivity 8.37 cm hr-1  
Sand Particle 93.26 mass percentage  
Clay Particle 3.64 mass percentage  
Field Width in Wind Direction 16.81 in m  
Start Time 11.92 hour of a day  
Water Flow Iteration Criterion 1.0E-5 in %  
Mass Balance Criterion for Water 5.0 in %  
Weather Data HourlyWeatherMay.txt  
Output Process MayDH1.txt  
Canopy Height 0.0 in cm

## June 2006

### A. Traveling gun

Max Time 48.0  
Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
Depth Applied 0.85 cm  
Total Ammoniacal N Concentration 0.712 in g L-1  
Manure pH 8.0  
Soil pH 7.2  
Dispersivity 0.4 cm  
Partition Coefficient 2.58 cm<sup>3</sup> g-1  
van Genuchten alpha 0.0135 cm-1  
van Genuchten n 1.3830  
Saturated Water Content 0.4553  
Residual Water Content 0.0834  
Saturated Hydraulic Conductivity 8.37 cm hr-1  
Sand Particle 93.3 mass percentage  
Clay Particle 3.6 mass percentage  
Field Width in Wind Direction 37.64 in m  
Start Time 10.75 hour of a day  
Water Flow Iteration Criterion 1.0E-5 in %  
Mass Balance Criterion for Water 5.0 in %  
Weather Data HourlyWeatherJune.txt  
Output Process Jun.txt  
Canopy Height 0.0 in cm

## July 2006

### A. Traveling gun

Max Time 96.0  
Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
Depth Applied 1.01 cm  
Total Ammoniacal N Concentration 0.562 in g L-1  
Manure pH 7.64  
Soil pH 7.25  
Dispersivity 0.4 cm  
Partition Coefficient 2.58 cm<sup>3</sup> g-1  
van Genuchten alpha 0.0135 cm-1  
van Genuchten n 1.3830  
Saturated Water Content 0.4553  
Residual Water Content 0.0834  
Saturated Hydraulic Conductivity 8.37 cm hr-1  
Sand Particle 93.3 mass percentage  
Clay Particle 3.6 mass percentage  
Field Width in Wind Direction 43.66 in m  
Start Time 11.33 hour of a day  
Water Flow Iteration Criterion 1.0E-5 in %  
Mass Balance Criterion for Water 5.0 in %  
Weather Data HourlyWeatherJul.txt  
Output Process Jul.txt  
Canopy Height 0.0 in cm

**B. Drag hose using sprinkler irrigation module**

Max Time 96.0  
Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
Depth Applied 1.04 cm  
Total Ammoniacal N Concentration 0.553 in g L-1  
Manure pH 7.74  
Soil pH 7.25  
Dispersivity 0.4 cm  
Partition Coefficient 2.58 cm<sup>3</sup> g-1  
van Genuchten alpha 0.0135 cm-1  
van Genuchten n 1.3830  
Saturated Water Content 0.4553  
Residual Water Content 0.0834  
Saturated Hydraulic Conductivity 8.37 cm hr-1  
Sand Particle 93.3 mass percentage  
Clay Particle 3.6 mass percentage  
Field Width in Wind Direction 24.61 in m  
Start Time 10.5 hour of a day  
Water Flow Iteration Criterion 1.0E-5 in %  
Mass Balance Criterion for Water 5.0 in %  
Weather Data HourlyWeatherJul.txt  
Output Process JulDH.txt  
Canopy Height 0.0 in cm

**C. Drag hose using flood irrigation module**

Max Time 96.0  
Irrigation Type 1 0---Sprinkler irrigation; 1---Flood irrigation  
Depth Applied 1.04 cm  
Total Ammoniacal N Concentration 0.553 in g L-1  
Manure pH 7.74  
Soil pH 7.25  
Dispersivity 0.4 cm  
Partition Coefficient 2.58 cm<sup>3</sup> g-1  
van Genuchten alpha 0.0135 cm-1  
van Genuchten n 1.3830  
Saturated Water Content 0.4553  
Residual Water Content 0.0834  
Saturated Hydraulic Conductivity 8.37 cm hr-1  
Sand Particle 93.3 mass percentage  
Clay Particle 3.6 mass percentage  
Field Width in Wind Direction 24.61 in m  
Start Time 10.5 hour of a day  
Water Flow Iteration Criterion 1.0E-5 in %  
Mass Balance Criterion for Water 5.0 in %  
Weather Data HourlyWeatherJul.txt  
Output Process JulDH1.txt  
Canopy Height 0.0 in cm

#### D. Other input files for sensitivity analysis

Max Time 96.0  
Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
Depth Applied 1.01 cm  
Total Ammoniacal N Concentration 0.67 in g L-1  
Manure pH 7.64  
Soil pH 7.25  
Dispersivity 0.4 cm  
Partition Coefficient 2.58 cm<sup>3</sup> g-1  
van Genuchten alpha 0.0135 cm-1  
van Genuchten n 1.3830  
Saturated Water Content 0.4553  
Residual Water Content 0.0834  
Saturated Hydraulic Conductivity 8.37 cm hr-1  
Sand Particle 93.3 mass percentage  
Clay Particle 3.6 mass percentage  
Field Width in Wind Direction 43.66 in m  
Start Time 11.33 hour of a day  
Water Flow Iteration Criterion 1.0E-5 in %  
Mass Balance Criterion for Water 5.0 in %  
Weather Data HourlyWeatherJul.txt  
Output Process JulANC+.txt  
Canopy Height 0.0 in cm

Max Time 96.0  
Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
Depth Applied 1.01 cm  
Total Ammoniacal N Concentration 0.45 in g L-1  
Manure pH 7.64  
Soil pH 7.25  
Dispersivity 0.4 cm  
Partition Coefficient 2.58 cm<sup>3</sup> g-1  
van Genuchten alpha 0.0135 cm-1  
van Genuchten n 1.3830  
Saturated Water Content 0.4553  
Residual Water Content 0.0834  
Saturated Hydraulic Conductivity 8.37 cm hr-1  
Sand Particle 93.3 mass percentage  
Clay Particle 3.6 mass percentage  
Field Width in Wind Direction 43.66 in m  
Start Time 11.33 hour of a day  
Water Flow Iteration Criterion 1.0E-5 in %  
Mass Balance Criterion for Water 5.0 in %  
Weather Data HourlyWeatherJul.txt  
Output Process JulANC-.txt  
Canopy Height 0.0 in cm

Max Time 96.0  
 Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
 Depth Applied 1.01 cm  
 Total Ammoniacal N Concentration 0.562 in g L-1  
 Manure pH 7.64  
 Soil pH 7.25  
 Dispersivity 0.4 cm  
 Partition Coefficient 3.87 cm<sup>3</sup> g-1  
 van Genuchten alpha 0.0135 cm-1  
 van Genuchten n 1.3830  
 Saturated Water Content 0.4553  
 Residual Water Content 0.0834  
 Saturated Hydraulic Conductivity 8.37 cm hr-1  
 Sand Particle 93.3 mass percentage  
 Clay Particle 3.6 mass percentage  
 Field Width in Wind Direction 43.66 in m  
 Start Time 11.33 hour of a day  
 Water Flow Iteration Criterion 1.0E-5 in %  
 Mass Balance Criterion for Water 5.0 in %  
 Weather Data HourlyWeatherJul.txt  
 Output Process JulPC+.txt  
 Canopy Height 0.0 in cm

Max Time 96.0  
 Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
 Depth Applied 1.01 cm  
 Total Ammoniacal N Concentration 0.562 in g L-1  
 Manure pH 7.64  
 Soil pH 7.25  
 Dispersivity 0.4 cm  
 Partition Coefficient 1.29 cm<sup>3</sup> g-1  
 van Genuchten alpha 0.0135 cm-1  
 van Genuchten n 1.3830  
 Saturated Water Content 0.4553  
 Residual Water Content 0.0834  
 Saturated Hydraulic Conductivity 8.37 cm hr-1  
 Sand Particle 93.3 mass percentage  
 Clay Particle 3.6 mass percentage  
 Field Width in Wind Direction 43.66 in m  
 Start Time 11.33 hour of a day  
 Water Flow Iteration Criterion 1.0E-5 in %  
 Mass Balance Criterion for Water 5.0 in %  
 Weather Data HourlyWeatherJul.txt  
 Output Process JulPC-.txt  
 Canopy Height 0.0 in cm

Max Time 96.0  
 Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
 Depth Applied 1.01 cm  
 Total Ammoniacal N Concentration 0.562 in g L-1  
 Manure pH 7.64  
 Soil pH 7.55  
 Dispersivity 0.4 cm  
 Partition Coefficient 2.58 cm<sup>3</sup> g-1  
 van Genuchten alpha 0.0135 cm-1  
 van Genuchten n 1.3830  
 Saturated Water Content 0.4553  
 Residual Water Content 0.0834  
 Saturated Hydraulic Conductivity 8.37 cm hr-1  
 Sand Particle 93.3 mass percentage  
 Clay Particle 3.6 mass percentage  
 Field Width in Wind Direction 43.66 in m  
 Start Time 11.33 hour of a day  
 Water Flow Iteration Criterion 1.0E-5 in %  
 Mass Balance Criterion for Water 5.0 in %  
 Weather Data HourlyWeatherJul.txt  
 Output Process JulPH+.txt  
 Canopy Height 0.0 in cm

Max Time 96.0  
 Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
 Depth Applied 1.01 cm  
 Total Ammoniacal N Concentration 0.562 in g L-1  
 Manure pH 7.64  
 Soil pH 7.07  
 Dispersivity 0.4 cm  
 Partition Coefficient 2.58 cm<sup>3</sup> g-1  
 van Genuchten alpha 0.0135 cm-1  
 van Genuchten n 1.3830  
 Saturated Water Content 0.4553  
 Residual Water Content 0.0834  
 Saturated Hydraulic Conductivity 8.37 cm hr-1  
 Sand Particle 93.3 mass percentage  
 Clay Particle 3.6 mass percentage  
 Field Width in Wind Direction 43.66 in m  
 Start Time 11.33 hour of a day  
 Water Flow Iteration Criterion 1.0E-5 in %  
 Mass Balance Criterion for Water 5.0 in %  
 Weather Data HourlyWeatherJul.txt  
 Output Process JulPH-.txt  
 Canopy Height 0.0 in cm

Max Time 96.0  
 Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
 Depth Applied 1.01 cm  
 Total Ammoniacal N Concentration 0.562 in g L-1  
 Manure pH 7.64  
 Soil pH 7.25  
 Dispersivity 0.4 cm  
 Partition Coefficient 2.58 cm<sup>3</sup> g-1  
 van Genuchten alpha 0.0135 cm-1  
 van Genuchten n 1.3830  
 Saturated Water Content 0.4553  
 Residual Water Content 0.0834  
 Saturated Hydraulic Conductivity 8.37 cm hr-1  
 Sand Particle 93.3 mass percentage  
 Clay Particle 3.6 mass percentage  
 Field Width in Wind Direction 43.66 in m  
 Start Time 11.33 hour of a day  
 Water Flow Iteration Criterion 1.0E-5 in %  
 Mass Balance Criterion for Water 5.0 in %  
 Weather Data HourlyWeatherJulWS+.txt  
 Output Process JulWS+.txt  
 Canopy Height 0.0 in cm

Max Time 96.0  
 Irrigation Type 0 0---Sprinkler irrigation; 1---Flood irrigation  
 Depth Applied 1.01 cm  
 Total Ammoniacal N Concentration 0.562 in g L-1  
 Manure pH 7.64  
 Soil pH 7.25  
 Dispersivity 0.4 cm  
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 Saturated Water Content 0.4553  
 Residual Water Content 0.0834  
 Saturated Hydraulic Conductivity 8.37 cm hr-1  
 Sand Particle 93.3 mass percentage  
 Clay Particle 3.6 mass percentage  
 Field Width in Wind Direction 43.66 in m  
 Start Time 11.33 hour of a day  
 Water Flow Iteration Criterion 1.0E-5 in %  
 Mass Balance Criterion for Water 5.0 in %  
 Weather Data HourlyWeatherJulWS-.txt  
 Output Process JulWS-.txt  
 Canopy Height 0.0 in cm

**APPENDIX B. OUTPUTS ON THE COMMAND SCREEN AFTER  
MODELING AMMONIA EMISSION**

## October 2005

### A. Traveling gun

Time Elapsed: 120.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 1.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.1685 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/oct.in  
Output File: output/Oct.txt  
Mass balance criteria satisfied

### B. Drag hose, sprinkler irrigation

Time Elapsed: 120.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.3273 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/octdh.in  
Output File: output/OctDH.txt  
Mass balance criteria satisfied

### C. Drag hose, flood irrigation

Time Elapsed: 120.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 0.0024 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.3922 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/octdh1.in  
Output File: output/OctDH1.txt  
Mass balance criteria satisfied

## May 2006

### A. Traveling gun

Time Elapsed: 96.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0478 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/may.in  
Output File: output/May.txt  
Mass balance criteria satisfied

## **B. Drag hose, sprinkler irrigation**

Time Elapsed: 96.0 hr  
Convergence check in water flow iteration: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0049 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/maydh.in  
Output File: output/MayDH.txt  
Mass balance criteria satisfied

## **C. Drag hose, flood irrigation**

Time Elapsed: 96.0 hr  
Convergence check in water flow iteration: true  
Water flow mass balance check: true : 0.0026 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0725 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/maydh1.in  
Output File: output/MayDH1.txt  
Mass balance criteria satisfied

## **June 2006**

### **A. Traveling gun**

Time Elapsed: 48.0 hr  
Convergence check in water flow iteration: true  
Water flow mass balance check: true : 3.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0097 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/jun.in  
Output File: output/Jun.txt  
Mass balance criteria satisfied

## **July 2006**

### **A. Traveling gun**

Time Elapsed: 96.0 hr  
Convergence check in water flow iteration: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0547 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/jul.in  
Output File: output/Jul.txt  
Mass balance criteria satisfied

**B. Drag hose, sprinkler irrigation**

Time Elapsed: 96.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0457 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/juldh.in  
Output File: output/JulDH.txt  
Mass balance criteria satisfied

**C. Drag hose, flood irrigation**

Time Elapsed: 96.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 0.0026 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0376 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/juldh1.in  
Output File: output/JulDH1.txt  
Mass balance criteria satisfied

**D. Traveling gun, for sensitivity analysis**

Time Elapsed: 96.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0547 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/julanc+.in  
Output File: output/JulANC+.txt  
Mass balance criteria satisfied

Time Elapsed: 96.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0547 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/julanc-.in  
Output File: output/JulANC-.txt  
Mass balance criteria satisfied

Time Elapsed: 96.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0547 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/julpc+.in  
Output File: output/JulPC+.txt  
Mass balance criteria satisfied

Time Elapsed: 96.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0547 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/julpc-.in  
Output File: output/JulPC-.txt  
Mass balance criteria satisfied

Time Elapsed: 96.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0547 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/julph+.in  
Output File: output/JulPH+.txt  
Mass balance criteria satisfied

Time Elapsed: 96.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0547 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/julph-.in  
Output File: output/JulpH-.txt  
Mass balance criteria satisfied

Time Elapsed: 96.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0519 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/julws+.in  
Output File: output/JulWS+.txt  
Mass balance criteria satisfied

Time Elapsed: 96.0 hr  
Convergence check in water flow interation: true  
Water flow mass balance check: true : 2.0E-4 %  
Ammoniacal N mass balance check: 0.0 %  
Mass Balance of Water: 0.0058 %  
Mass Balance of Ammoniacal N: 0.0 %  
Input File: input/julws-.in  
Output File: output/JulWS-.txt  
Mass balance criteria satisfied