

## ABSTRACT

Title of Dissertation:                   ASSESSING THE EFFECTIVENESS OF  
VEGETATIVE ENVIRONMENTAL  
BUFFERS IN MITIGATING POULTRY-  
EMITTED AIR POLLUTANTS

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The noticeable expansion of the concentrated feeding operation in the poultry industry has been putting considerable stress on the atmospheric environment and is also a public health concern. Poultry manure has been widely identified as a potential water pollutant source by regulators and researchers. However, less is known about the atmospheric emissions from poultry houses which includes particulate matter (PM), ammonia, and volatile organic compounds (VOCs). Vegetative Environmental Buffers (VEBs) have been introduced as a possible air pollutant migration technology to poultry farms. VEBs are vegetation designed to serve as a visual screen and consist of trees, shrubs, grass and other plants. Preliminary studies suggested that VEBs are able to reduce air pollutant emissions, however quantitative studies are needed to improve the overall design and assess their effectiveness. In this project, field experiments at three different poultry houses were conducted to quantify the efficacy of VEBs in migrating air pollutants. Time-integrated particulate, ammonia, and air samples were collected at multiple locations and heights. A small-scale Gaussian plume model was used to predict pollutant emissions from a poultry house without a VEB under the same meteorological conditions. Results showed significant TSP, PM<sub>10</sub>, PM<sub>2.5</sub>, and NH<sub>3</sub> concentration decreases behind the VEB. Methanol, acetone, and ethanol were the most abundant VOCs emitted from the poultry house, but these compounds can also contribute to the formation of ground level ozone. VEBs were showed promising potential in decreasing the ozone formation potential of VOCs. This project will contribute to the National Conservative Practice Standard (NCPS # 380 or # 420) by providing important expertise to the design and proper installation of VEBs. The work has been presented in extension and outreach programs.

ASSESSING THE EFFECTIVENESS OF VEGETATIVE ENVIRONMENTAL  
BUFFERS IN MITIGATING POULTRY-EMITTED AIR POLLUTANTS

by

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Dissertation submitted to the Faculty of the Graduate School of the  
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## Dedication

This dissertation is dedicated to the love of research.

My thanks and appreciation to Dr. Alba Torrents and Dr. Cathleen J. Hapeman for preserving with me as my advisors throughout five years of brainstorming. Their wisdom and strong mind, as female scientists, have inspired me profoundly.

The members of my dissertation committee, Dr. Allen Davis, Dr. Hong Li, and Dr. Xin He, have generously given their time and expertise to better my work. I thank them for their contribution and their good-natured support.

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# Table of Contents

Dedication .....	ii
Acknowledgements .....	iii
Table of Contents .....	iv
List of Tables .....	vi
List of Figures .....	vii
Chapter 1: Introduction .....	1
Concentrated animal feeding Operation (CAFO) .....	1
History .....	1
Poultry industry .....	2
Major air pollutant emissions from the poultry house .....	4
Ammonia .....	8
Volatile organic compound (VOC) .....	12
Air pollutant emission reduction approach .....	15
Current technique .....	15
Vegetative environmental buffer (VEB) .....	17
Chapter 2: Objective .....	20
Chapter 3: Particulate matter (PM) reduction by Vegetative environmental buffer (VEB): TSP, PM <sub>10</sub> , and PM <sub>2.5</sub> .....	21
Abstract .....	21
Introduction .....	21
Materials and methods .....	23
Site description .....	23
Field sampling campaign set-ups .....	24
Meteorological measurements .....	25
Particulate matter collection and analysis .....	26
Gaussian plume model analysis .....	26
Statistical analysis .....	27
Results and discussion .....	28
Meteorological conditions .....	28
PM concentrations .....	30
Correlation between TSP, PM <sub>10</sub> , PM <sub>2.5</sub> concentrations and meteorological factors .....	36
Ground-level PM concentration reduction .....	37
Correlation between ground-level PM concentration reduction ratios and metrological factors .....	39
Conclusions .....	41
Chapter 4: Assessment of Vegetative Environmental Buffer (VEB) to mitigate poultry-emitted ammonia and PM <sub>2.5</sub> .....	42
Abstract .....	42
Introduction .....	42
Materials and methods .....	46
Site description .....	46
Field sampling campaign set-ups .....	47

Meteorological measurements .....	48
Particulate matter sampling and analysis .....	49
Ammonia sampling and analysis .....	49
Gaussian plume model analysis .....	50
Statistical analysis .....	51
Results and discussion .....	52
Meteorological condition .....	52
NH <sub>3</sub> concentrations .....	52
PM <sub>2.5</sub> concentrations .....	56
Correlation between PM <sub>2.5</sub> , NH <sub>3</sub> , and meteorological factors .....	59
Ground-level NH <sub>3</sub> concentration reduction .....	60
Ground-level: PM <sub>2.5</sub> concentration reduction .....	64
Correlation between ground-level PM <sub>2.5</sub> concentration reduction ratio and NH <sub>3</sub> concentration reduction ratio and meteorological factors .....	66
Conclusions .....	67
Chapter 5: Poultry house emissions: source for volatile organic compounds with ozone formation potential .....	68
Abstract .....	68
Introduction .....	68
Materials and Methods .....	71
Site description .....	71
Air sampling .....	72
Sample analyses .....	74
Statistical analyses .....	75
Results and discussions .....	76
Methanol .....	76
Ethanol and acetone .....	79
Other VOCs .....	80
Ozone formation potential .....	82
Chapter 6: Conclusion .....	85
Appendices A: Chapter 3 supplementary information .....	86
Appendices B: Chapter 4 supplementary information .....	102
Appendices C: Chapter 5 supplementary information .....	107
Glossary .....	128
Bibliography .....	129

## List of Tables

Chapter 1	
Table 1 .....	5
Table 2 .....	11
Chapter 3	
Table 1 .....	29
Table 2 .....	36
Table 3 .....	36
Table 4 .....	41
Chapter 4	
Table 1 .....	52
Table 2 .....	59
Table 3 .....	60
Table 4 .....	66
Table 5 .....	67
Chapter 5	
Table 1 .....	84



# List of Figures

Chapter 1	
Figure 1 .....	3
Figure 2 .....	4
Figure 3 .....	7
Figure 4 .....	9
Figure 5 .....	10
Figure 6 .....	11
Figure 7 .....	13
Figure 8 .....	14
Figure 9 .....	17
Figure 10 .....	18
Chapter 3	
Figure 1 .....	24
Figure 2 .....	25
Figure 3 .....	32
Figure 4 .....	38
Figure 5 .....	30
Chapter 4	
Figure 1 .....	44
Figure 2 .....	45
Figure 3 .....	48
Figure 4 .....	53
Figure 5 .....	57
Figure 6 .....	62
Figure 7 .....	65
Chapter 5	
Figure 1 .....	73
Figure 2 .....	78
Figure 3 .....	80
Figure 4 .....	81

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# Chapter 1: Introduction

## Concentrated animal feeding Operation (CAFO)

### History

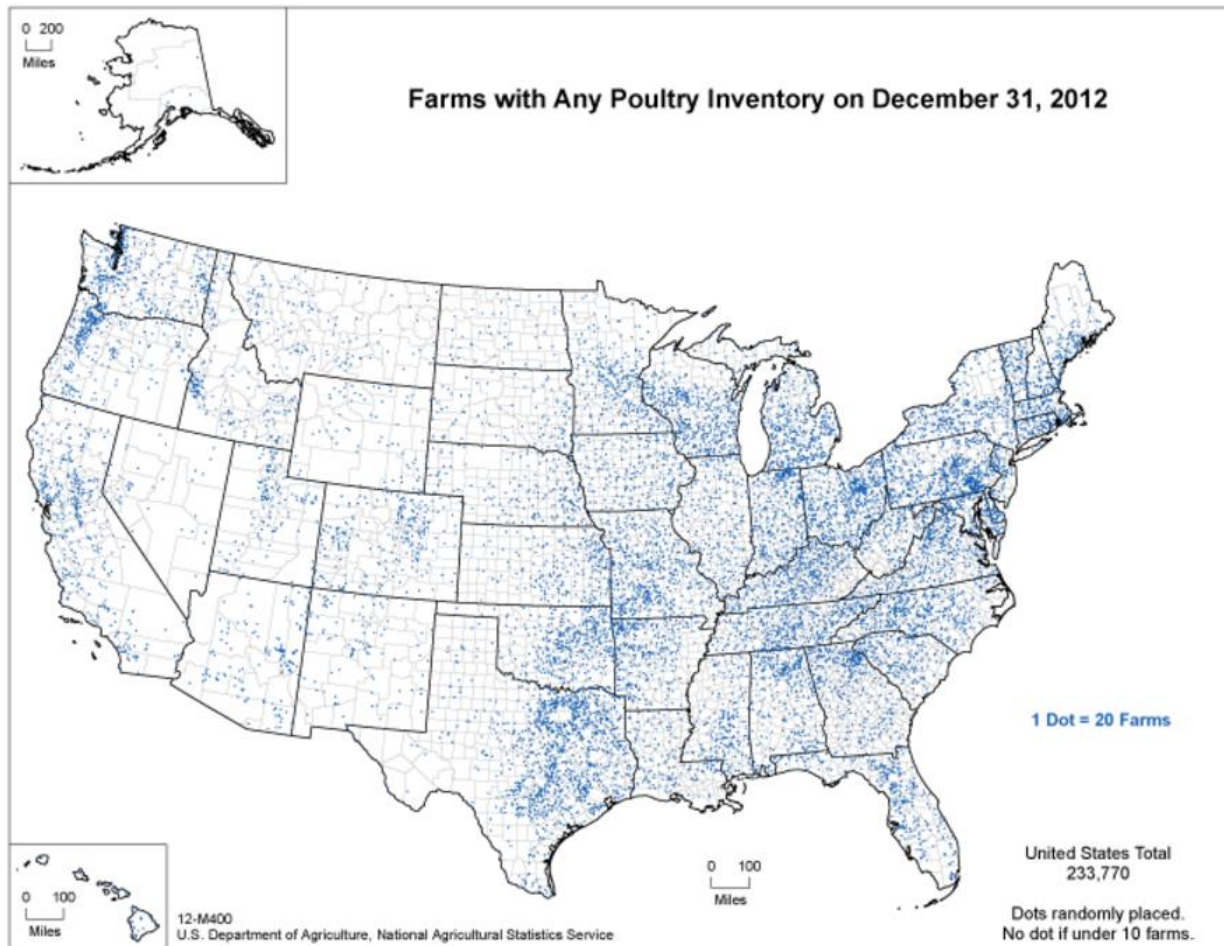
Animal feeding operations (AFOs) are agricultural operations where domestic animals are fed and kept in confined facilities with the following conditions: i) animals have been, are, or will be stabled or confined and fed or maintained for a total of 45 days or more in any 12-month period; and ii) crops, vegetation, forage growth, or post-harvest residues are not sustained in the normal growing season over any portion of the lot or facility (EPA, 2017). A CAFO is large-scaled AFO and is categorized based on the type and number of contained animals. With proper management, CAFOs can provide low-cost meat, dairy, and egg products in a relatively short time. Accordingly, CAFOs promote the local economy and increase the employment rate by using locally produced material and labors and contributing to the tax expenditures and leading to public infrastructure developments (CDC, 2010).

However, the public has become concerned about CAFOs because of the potential negative effects on public health and the environment. Research has demonstrated that CAFOs are associated with degraded air quality, contaminated waterbodies, and even the spread of diseases. CAFO manure is major contamination source as it contains a number of potential pollutants, such as nitrogen and phosphorus compounds, volatile organic compounds (VOCs), hormones, antibiotics, pathogens, and particles (CDC, 2010). Most manure produced by CAFOs is applied to land eventually. This land application can result in leaching of contaminants to waterbodies, releasing odorous gases to the air, and distributing infectious pathogens (Cole, Todd, & Wing1, 2000). In the 1972 Clean Water Act, Section 502, AFOs were first identified as

potential pollutant sources for the aquatic environment. As a consequence, a permit program: National Pollutant Discharge Elimination System (NPDES), was initiated by US EPA for AFO/CAFO effluent. CAFOs are now regulated by NPDES which has been revised twice, once in 2003 and again in 2008 (US EPA, 2017).

### Poultry industry

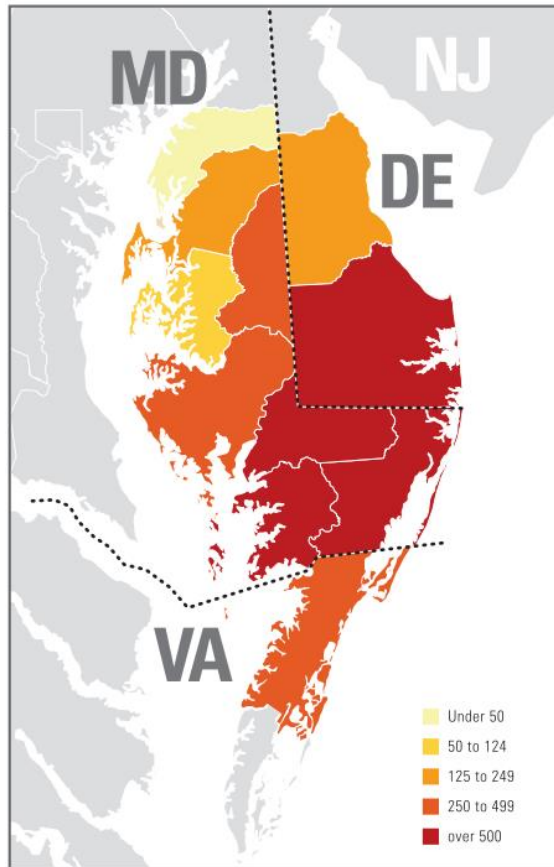
The US poultry industry is the largest in the world, and it is also the single largest meat-producing industry in the US. From 1985 to 1995, the number of broilers nearly doubled from 4.3 billion to 7.3 billion nationally. Since then, broiler production has continued to increase but at a slower rate. In 2016, the number of broilers produced was 8.8 billion, an 15% increase over 2006, and yielded 53.4 billion pounds of product with a value of more than \$28,700,000 (USDA, 2017). However, over the last 20 years, the number of broiler farms in the US declined slightly from 27,654 to 27,091 (USDA National Agricultural Statistics Service 2016). These contradictory statistical data confirm that poultry production is shifting from traditional farms to larger production facilities. Today, most poultry farms are CAFOs.



**Figure 1.** Poultry farm inventory in the US, 2012 ((USDA National Agricultural Statistics Service, 2016).

As shown in **Fig 1**, the Mid-Atlantic region of the United States has many CAFOs due to the large markets from New York to Washington DC. The density of chicken produced in the Delmarva area is especially high (**Fig 2.**), and in 2016, Virginia, Maryland, Delaware, and Pennsylvania together produced almost 9% of the broilers in the US (USDA National Agricultural Statistics Service, 2017). These four states make up a developed broiler belt (areas where chickens outnumber people) in the Chesapeake Bay region. In Delaware, for example, 270 chickens were produced per person annually in 2010 (Pew Environment Group, 2011). This rapid expansion and consolidation of concentrated poultry operations has raised concerns among

the local jurisdictions and environmental groups about the pollutant emissions and the negative impacts on the public welfare.



**Figure 2.** Density of broiler chickens per acre of cropland on Delmarva in 2007 (Pew Environment Group, 2011).

Major air pollutant emissions from the poultry house

In the recent decades, concern has been raised that the expansion of the US poultry industry emits air pollutants introducing environmental stress and jeopardizing human health. Studies have shown that poultry air emissions include particulate matter, hydrogen sulfide, methane, ozone, ammonia, and volatile organic compounds (VOCs) (Adrizal et al., 2008; Roumeliotis, Dixon, Van Heyst, Heyst, & Van Heyst, 2010; Trabue et al., 2010). The potential harmful effects from poultry-emitted air pollutants are listed in **Table 1**. The main source of

these pollutants is poultry litter, which is a mixture of manure, waste bedding, sate food, fertilizer and crop residues, and feathers (Carey, Lacey, & Mukhtar, 2004).

**Table 1.** Potential importance of air emissions from animal feeding operations (National Research Council, 2003)

Emission	Area and scale of concern		Primary effects
	Global, naitonal and reginal	Local property line or nearest dwelling	
NH <sub>3</sub>	Major	Minor	Atmospheric deposition, haze
N <sub>2</sub> O	Significant	Insignificant	Green house gas, climate change
NO <sub>x</sub>	Significant	Minor	Haze, atmospheric depositon, smog
CH <sub>4</sub>	Significant	Insignificant	Green house gas, climate change
VOC	Insignificant	Minor	Quality of human life
H <sub>2</sub> S	Insignificant	Significant	Quality of human life
PM, PM <sub>10</sub>	Insignificant	Significant	Haze
PM <sub>2.5</sub>	Insignificant	Significant	Health, haze
Odor	Insignificant	Major	Quality of human life

There are no specific regulations for air emissions from poultry houses, however, three atmospheric related laws are potentially applicable: the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, also known as the Superfund Act), the Emergency Planning & Community Right to Know Act (EPCRA), and the Clean Air Act (CAA).

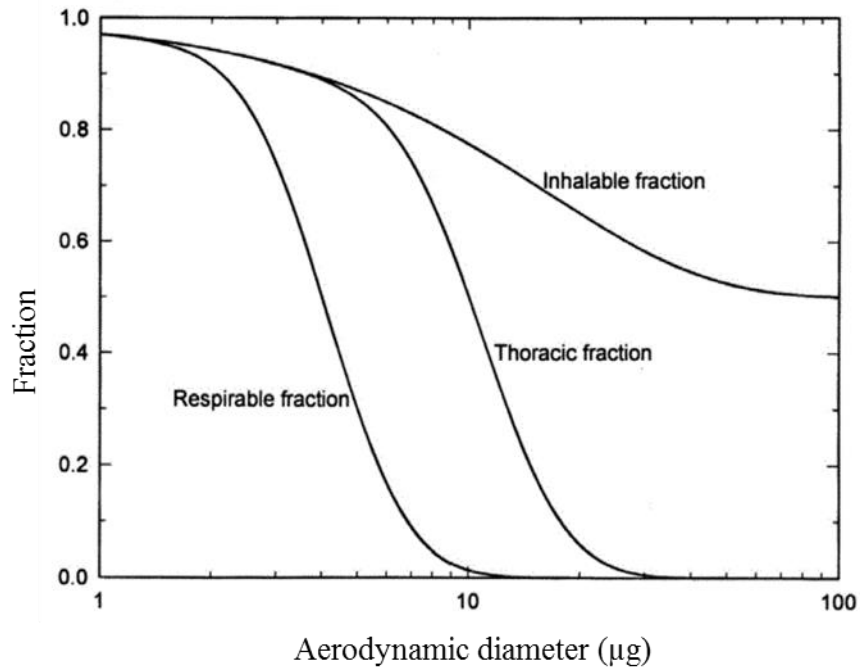
Only CAFOs that are categorized as large are required to report any ammonia or hydrogen sulfide emission events of 100 pounds or more in a 24-hour period under EPCRA (CDC, 2010).

#### Particulate Matters (TSP, PM<sub>2.5</sub> and PM<sub>10</sub>)

Particulate matter is defined by the US EPA as a complex mixture of suspended particles with different physical, chemical, and biological characteristics (EPA, 2016b). It is categorized into three groups: total suspended particulate (TSP) with approximate particle diameter of less than 50-100  $\mu\text{m}$ ; inhalable coarse particles (PM<sub>10</sub>) with an aerodynamic diameter of less than 10  $\mu\text{m}$ ; and inhalable fine particles (PM<sub>2.5</sub>) with an aerodynamic diameter of less than 2.5  $\mu\text{m}$  (**Fig. 3**).

Particulate matter size is directly linked to the potential for causing health problems. Smaller particles that are inhaled can penetrate deeper into the respiratory system and can harm the cardiovascular system. Symptoms include irritation of the airways, lung malfunction, irregular heartbeat, aggravated asthma, and even premature death. Children and older adults are usually the most vulnerable. In addition to the health effects, PM affects the atmosphere. Under humid conditions, particles encounter sunlight and cause haze decreasing visibility. PM can also contribute to acid rain which causes damage to human health, natural ecosystems, and anthropological structures (EPA, 2016b).

PM<sub>2.5</sub> and PM<sub>10</sub> are criteria air pollutants regulated under the Clean Air Act. The National Ambient Air Quality Standards set limits for PM<sub>2.5</sub> concentrations in the atmosphere for public health (primary standard) and for public welfare (secondary standard). For PM<sub>2.5</sub>, the primary standard is 12  $\mu\text{g}/\text{m}^3$  and the secondary standard is 15  $\mu\text{g}/\text{m}^3$  for an annual mean, while the primary and secondary standard for 24 hours is 35  $\mu\text{g}/\text{m}^3$ . The 24-hour and the annual primary and secondary standards for PM<sub>10</sub> is 150  $\mu\text{g}/\text{m}^3$  (EPA, 2016b).



**Figure 3.** Summary of sampling inhalable, thoracic, and respirable fraction of PM (ACGIH, 2005)

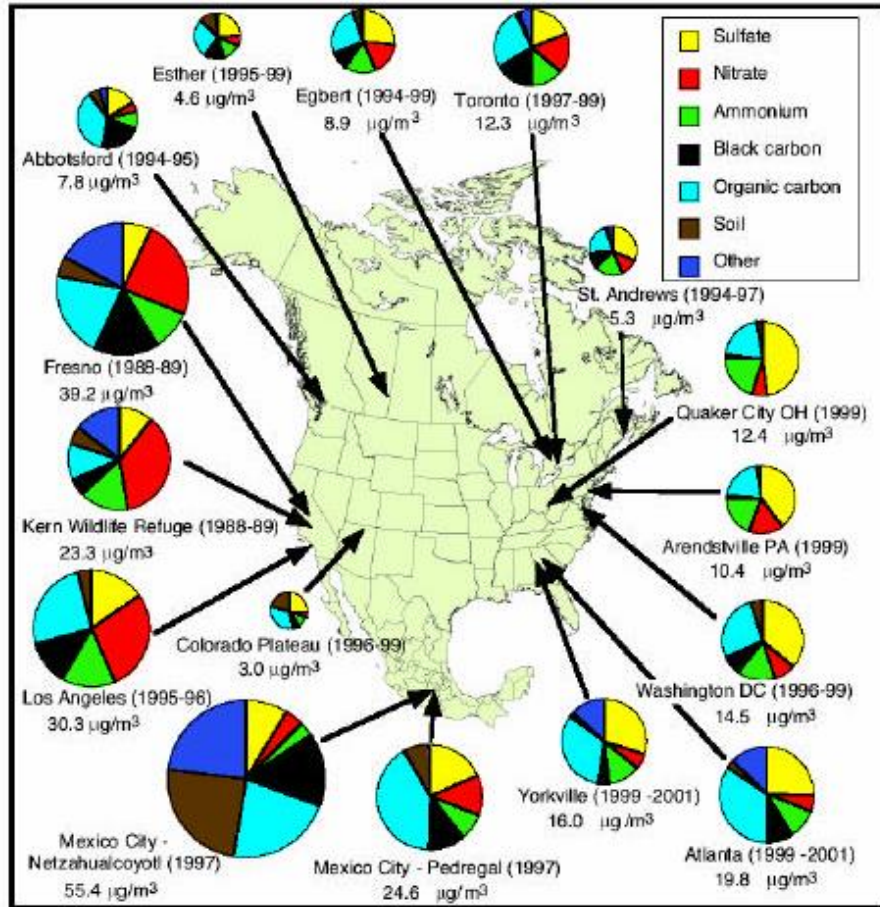
Particulate matter emitted from the poultry houses has been identified as down from feathers, mineral crystals from uric acid, and litter. The type of litter and its moisture content can also influence PM concentration (Patterson & Adrizal, 2005b). Studies have been conducted on measuring the PM emission factor of poultry houses. Lim (2003) reported emission factors of a production layer operation for PM<sub>2.5</sub>, PM<sub>10</sub> and TSP of  $1.1 \pm 0.3$ ,  $16 \pm 3.4$ , and  $63 \pm 15$  g/d-AU respectively (AU = 500 kg). Lacey (2003) reported emission factors of a commercial broiler house for PM<sub>10</sub> and TSP of 13 g and 245 g/d-AU. Roumeliotis (2007) reported emission factors for five and six week production cycles of a commercial broiler house for PM<sub>10</sub> of 4.6 and 5.9 g/d-AU, and for PM<sub>2.5</sub> of 0.8 and 1.4 g/d-AU respectively. The National Emission Inventory and Project Task Group (NEIPTG) developed general emission factors for TSP, PM<sub>2.5</sub>, and PM<sub>10</sub> of 0.4, 0.26, and 0.04 g/bird respectively, for all types of poultry operations (Beaulieu et al., 1999).



## Ammonia

Ammonia is the most abundant alkaline gas in the atmosphere. It is also one of the most important precursors of secondary fine particle ( $PM_{2.5}$ ) pollutants. Interactions between ammonia and acidic gases, such as sulfuric acid, nitric acid, and hydrochloric acid, result in the rapid formation of fine particles (**Eqs 1-3**). The formed particles are most likely to be ammonium sulfate, ammonium bisulfate, ammonium nitrate, and ammonium chloride (Erisman & Schaap, 2004). Reaction of  $NH_3$  with sulfuric acid or ammonium bisulfate is favored over reaction with nitric acid. Therefore, as shown in **Fig. 4**, most of the aerosol ammonium is associated with sulfate ion. In the western states, where sulfate level is low and nitrogen oxide emission is high, ammonia will favor the reaction with nitric oxides (EPA, 2004; McMurry, Shepherd, Vickery, & NARSTO., 2004). The formation of these particulates prolongs ammonia existence in the atmosphere and therefore affects geographic distribution of acid deposition. Moreover, the emitted ammonia is subsequently deposited to the soil and water ecosystems, and will influence the environment as a whole.





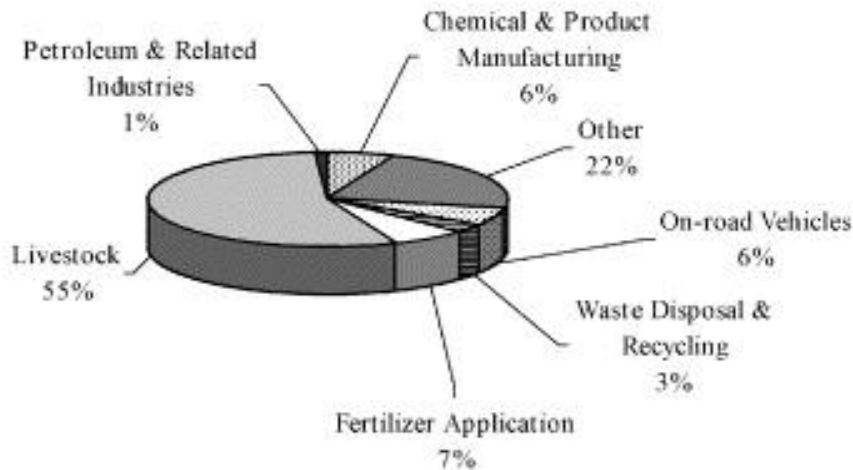
**Figure 4.** Composition of PM<sub>2.5</sub> at representative urban and rural locations (McMurry et al., 2004).

Ammonia emissions to the air are also considered a threat to human health. Inhaling low-concentration of gaseous ammonia can cause symptoms such as rhinorrhea, chest tightness, cough, and eye irritation. High concentration ammonia exposure can result in lung diseases, permanent blindness, or even death (ATSDR, 2011).

Regulations and recommendations have been proposed to protect people from ammonia exposure. Occupational Safety and Health Administration (OSHA) has set an 8-hour exposure limit of 25 ppm and a short-term (15-minute) exposure limit of 35 ppm for ammonia in the workplace. National Institute for Occupational Safety and Health (NIOSH) recommends that the level in workroom air be limited to 50 ppm for 5 minutes of exposure.

The largest contributor of ammonia is agricultural activities. In 1990, the total global ammonia emission was estimated to be 54 Tg N/yr, in which domestic animals emitted of 21.7 Tg N/yr. This is almost 50% contribution of total the global emission (Bouwman et al., 1997). More recent estimates indicate the poultry-emitted ammonia will contribute more than 30% of the total livestock ammonia emissions (EPA, 2004). Ammonia comes from poultry manure and house bedding inside poultry houses. The manure contains uric acid, which is a by-product of protein metabolism in poultry. The uric acid is broken down by microorganisms in the litter, which releases ammonia (Bachrach, 1957).

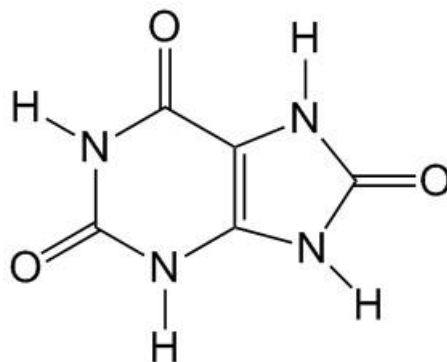
**Ammonia Emission Inventory: National Particulates Inventory (E.H. Pechan & Associates)**



**Figure 5.** Ammonia emission inventory for the United States in 1990 (Anderson, Strader, & Davidson, 2003).

**Table 2.** Summary of ammonia emission from US animal husbandry operations (EPA, 2004)

Animal Group	Ammonia Emissions (tons/year)				
	2002	2010	2015	2020	2030
Dairy	506,295	513,369	497,023	494,556	495,927
Beef	595,701	627,023	625,657	721,274	665,567
Poultry	602,587	588,037	653,581	698,594	788,659
Swine	389,607	440,187	464,894	480,108	469,996
Sheep	22,530	NE	NE	NE	NE
Goats	12,726	NE	NE	NE	NE
Horses	64,669	NE	NE	NE	NE
Total	2,194,113	2,168,616	2,241,154	2,313,477	2,420,150

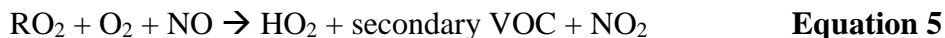


**Figure 6.** The chemical structure of uric acid.

Studies have been carried out to measure the ammonia emission factor for poultry houses. Lacey (2003) reported an average ammonia emission factor (EF) of a broiler house in the southern U.S. over a 49-day production period as 0.63 gNH<sub>3</sub>-N bird<sup>-1</sup>d<sup>-1</sup>. Siefert et al. (2004) reported an average ammonia emission factor of a broiler house in Delmarva area over a 6-week production period as 0.74 gNH<sub>3</sub>-N bird<sup>-1</sup>d<sup>-1</sup>. They furthered reported that during weeks 3, 4, and 5 of the 6-week grow-out period, the emission factor ranged from 0.27 to 2.17g NH<sub>3</sub>-N bird<sup>-1</sup>d<sup>-1</sup> with a mean of 1.18 g NH<sub>3</sub>-N bird<sup>-1</sup>d<sup>-1</sup>. Wheeler et al., (2006A) have developed a practical formula to calculate the emission factor based on the age of the bird as 0.031 (±0.0011, std error) \* age of the bird for birds that are 1 to 63 days old. The results are quite different due to the differences between the boiler house style, management, equipment selection, maintenance, and other factors. The recommended broiler emission factor for U.S. animal agriculture is reported as 0.18 kgN-NH<sub>3</sub> bird<sup>-1</sup> yr<sup>-1</sup>(Faulkner & Shaw, 2008).

#### Volatile organic compound (VOC)

Volatile organic compounds (VOCs) are considered important precursors for ground-level ozone formation. Under the sunlight, VOCs react with hydroxyl radicals (OH•) and nitrogen oxides and from ground-level ozone (**Eqs 4 - 8**) (Haagen-Smit, 1952). Therefore, decreasing the amount of VOCs released to the atmosphere is critical to reducing potential ozone pollution.

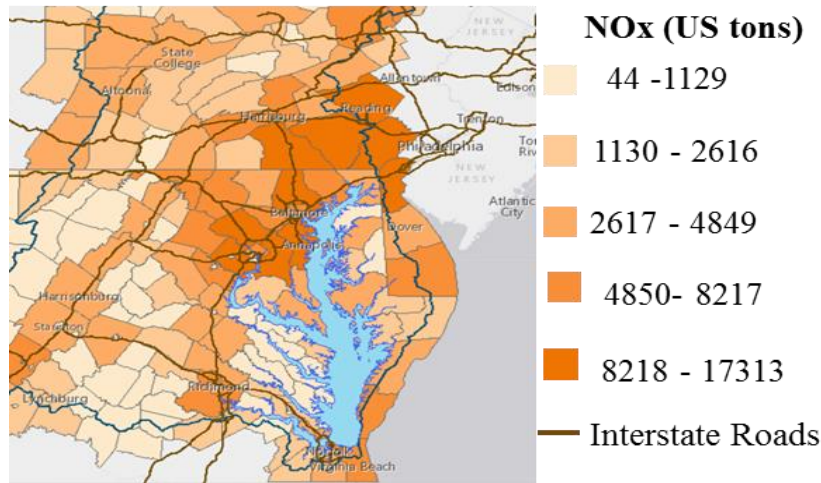


Ground-level ozone is one of the six criteria air pollutants identified in the Clean Air Act by US EPA. As the major ingredient in the ‘smog’, ground-level ozone can jeopardize human welfare and health, as well as ecosystems and other biota (USEPA, 2016). Ozone concentrations can reach unhealthy levels when the temperature is high and few or no clouds are present with little or no wind. The ozone season, when average ozone level is the highest, usually occurs from April to October. Ground-level ozone has been regulated by the National Ambient Air Quality Standards (NAAQS) set by EPA. In 2015, the EPA strengthened the NAAQS for ground-level ozone to 70 ppb averaged over 8-hours (USEPA, 2016). Since ground-level ozone forms when nitrogen oxides (NO<sub>x</sub>) and VOCs react in the presence of UV light (sunlight), this updated ozone standard will likely to introduce more strict regulations on NO<sub>x</sub> and VOCs.



**Figure 7.** Counties in Chesapeake Bay region, blue highlight areas, that did not meet the NAAQS of 70 ppb (averaged over 8-hrs) for ground-level ozone based on 2012-2014 data (EPA, 2015a).

The Chesapeake Bay is the largest estuary in the US and has an airshed that is influenced well beyond the six states of the watershed (Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and the District of Columbia). Some counties in the in the bay area did not meet the NAAQS for ground level ozone. It is likely that EPA will designate some bay area as nonattainment areas in late 2017 (EPA, 2015a). **Fig.7** shows the counties with monitors that did not meet the new EPA ground-level ozone requirement within Chesapeake Bay area. Electric power plants and traffic contribute significantly to the atmospheric deposition of NOx in the Bay area and increasing the potential to for ground-level ozone. **Fig.8** shows the mobile source emissions of NOx with the interstate roads as an important source. Thus, it is necessary to understand the VOC emissions around the Bay area and to explore and strategize approaches to control ozone formation.



**Figure 8.** Mobile source emission of NOx (tons) in Chesapeake Bay area based on National Emissions Inventory 2011. (US EPA, REG 03, 2017)

A large number of CAFO-emitted VOCs have been detected and quantified. A total of 324 VOCs and seven fixed gases from swine facilities have been listed and categorized (Schiffman, Bennett, & Raymer, 2001). The VOCs identified were volatile fatty acids, alcohols, aldehydes, amides, amines, aromatics, esters, ethers, fixed gases, halogenated hydrocarbons,

hydrocarbons, ketones, nitriles, other nitrogen containing compounds, phenols, sulfur containing compounds, and steroids. VOC emission rates have been investigated by a few studies about swine facilities. The reported data ranged from 3.0 to 176.5 mg d<sup>-1</sup> kg<sup>-1</sup> pig at swine finishing barns and from 2.3 to 45.2 g d<sup>-1</sup> m<sup>-2</sup> at manure storages. The significant difference is due to the variable manure management systems, barn structural designs and ventilation rates (Ni, Robarge, Xiao, & Heber, 2012). The most abundant VOCs reported as acetic acid of 830 µg/m<sup>3</sup>, 2,3-butanedione of 681 µg/m<sup>3</sup>, methanol of 196, acetone of 105 µg/m<sup>3</sup>, and ethanol of 102 µg/m<sup>3</sup> (Trabue et al., 2010).

### *Air pollutant emission reduction approach*

#### Current technique

In recent years many researchers have been assessing different technologies and processes to minimize the effect of CAFOs on air quality. Current strategies to control the air pollutant emissions from the broiler houses include dietary management, litter amendments, filter and bio-filters, electrostatic precipitators, vegetative environmental buffers, and acid scrubbers.

Dietary management can manipulate the gas emissions from the boilers by changing the microbiological environment of the bird digestive track and nutrient composition of feces. Studies have shown reduced ammonia release by increasing N utilization in animal diets (Carew, 2010; Ndegwa, Hristov, Arogo, & Sheffield, 2008). Matching diet to the amino acid or crude protein requirements of animals can decrease the N content in the waste, however the synthetic food additives are relatively pricy and it is not easy to balance other feed ingredients.

Litter amendments range from alum, aluminum chloride, sodium bisulfate, ferrous sulfate, and fly ash (Choi & Moore, 2008). Its primary function is controlling ammonia



volatilization from poultry litter. Most broiler houses in the US are using litter amendments all year, yet lower cost and higher efficiency are still the reasons people are seeking better approaches and materials for air pollutant removal.

Fibrous filters are the most common air cleaning devices and can trap dust and odor associated compounds (Ullman, Mukhtar, Lacey, & Carey, 2004). The problem of filtration is the dust and feathers in broiler facilities can clog the filter with time, and it is not efficient to clean or replace the filters regularly.

Bio-filters provide medium for microbial communities that can degrade odorous compounds. Bio-filters usually consist of natural porous materials, such as soil, compost, activated carbon, bark, and clay. They have different designs due to the target air pollutants. The systems showed significant removal of hydrogen sulfide, methane thiol, dimethylsulfide, and dimethyldisulfide (Cho, Hirai, & Shoda, 1991a; Cho, Hirai, & Shoda, 1991b; Ullman et al., 2004). However, the cost of the filters, electricity, media replacement, inspection, and general maintenance are still concerns of employing these systems.

An electrostatic precipitator (ESP) is also called an electrostatic air cleaner. It is a particulate matter collection device that uses the force of electrostatic charge to capture the particles. Studies have used ESP for poultry dust control and showed overall dust removal efficiency from 37% to 79% (Chai et al., 2009).

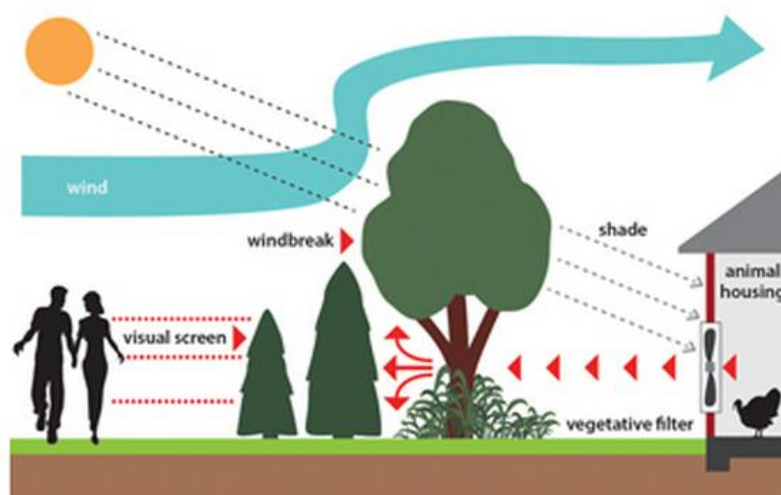
The acid scrubbers allow the poultry exhaust to pass through a scrubbing liquid (water and diluted acids,) in order to minimize the emission of particulate matter, ammonia, and other odorous compounds (R. Melse & Ogink, 2005). Cost has been the problem for wider spread employment of this method. Recent improvements in affordable multi-scrubbers with relatively

high air pollutant removal efficiencies have been made, which may allow more expanded utilization.

#### Vegetative environmental buffer (VEB)

While all the above methods have been studied, cost-efficient technologies to reduce air pollutants from poultry houses are limited. Vegetative environmental buffers (VEBs), one of the most promising low-cost methods, have been introduced to the poultry industry. Studies have reported that VEBs have potential to reduce ammonia, particulate matter, and odor emissions from the poultry houses (Patterson et al., 2008; Adrizal et al., 2008; Patterson, et al., 2005;).

A VEB, which is also referred to as a windbreak or a shelterbelt, consists of trees, shrubs, grass, and other plant materials. It is designed to be as a visual screen around the poultry houses and contributes to a positive perception about poultry industry by the general public (**Fig. 9**). It helps the poultry industry to create a more friendly image to nearby residential areas, as well as a more harmonious neighbor relations.



**Figure 9.** Vegetative buffer diagram (Patterson & Adrizal, 2005a)

Considering the direct contact of the exhaust from the poultry houses, all the air pollutants will have negative effects on the plants. With regards to the components of the VEBs, plant material specialists from Natural Resources Conservation Service (NRCS) National Plant Materials Center (PMC) have suggested the preferable plant species under expected intensive atmospheric environments for different regions. In addition, plant species differ significantly in their ability to trap airborne pollutants. For example, in Pennsylvania, poplar, hybrid willow, and Streamco willow are the preferable species for trapping ammonia, whereas spruce and hybrid willow are more efficient for trapping the particulate matter or odor (Adrizar et al., 2008). In the preliminary observations of particulate matter emissions experiments, VEBs can physically intercept and capture particles and other aerosols (**Fig. 10**). Studies have also shown that plant foliage can trap ammonia and act as a biological sink after the capture. The plants closer to the emission source were found to have a larger nitrogen concentration in the foliage (Patterson et al., 2008).



**Figure 10.** Preliminary observation of VEBs a) before particulate matter emissions, b) after particulate matter emissions (photo credit Q. Yao).

The distance between the buffers and the exhaust sources is also another important parameter to take into account. Early studies have suggested that the distance between buffer and

the ventilation fan should ten times the diameter of the fan. Other studies have showed that VEBs that are 15 m from the source have a better capability of improving odor dispersion (Lin, Barrington, Nicell, Choiniere, & Vezina, 2006; Tyndall & Colletti, 2007). However, Willis et al. (2017a, 2017b) used LiDAR to examine the fate of particulate matter released in front of a VEB, and discovered that one of the most important variables in VEB efficiency was the turbulent kinetic energy. These results are consistent with earlier findings where turbulence has been shown to be the dominant component controlling air pollutant emissions (Prueger, Eichinger, Hipps, Hatfield, & Cooper, 2008).

## Chapter 2: Objective

The main objective of this project was to assemble a multi-disciplined research team to develop methodologies and approaches to conduct a holistic investigation on the effectiveness of VEB in removing air pollutants, including particulate matters, ammonia, and VOCs emitted from poultry houses. This project will contribute to the National Conservative Practice Standard (NCPS # 380 or # 420) by providing important expertise to the design and proper installation of VEBs. The work has been presented in extension and outreach programs. This entire project leverages the collaborative efforts from University of Delaware, University of Maryland, Oklahoma State University, The Pennsylvania State University, and several USDA-Agriculture Research Center sites. Experimental research was conducted to examine the broiler farm emissions in , Delaware and Pennsylvania with with and without well-established VEBs. The performance of each experimental site was recorded and analyzed.

As part of my PhD research, my goal was to obtain a better understanding of the efficacy of VEBs in mitigating ammonia, particulate matters (PM), and volatile organic compounds (VOCs) emissions. In order to achieve this objective, I worked closely with the cooperators. I was in charge of collecting air (for VOCs analysis), PM (including total suspended particles, PM<sub>2.5</sub> and PM<sub>10</sub>), and ammonia samples simultaneously from different poultry houses. My specific objectives were to standardize sample collections and analytical protocols for sample analysis, to analyze the results, to assess pollutant emission profile, and the examine the VEB effectiveness in reducing the pollutants in the atmosphere. The results are intended to be used for optimizing VEBs designs. Overall, the expectation is to provide poultry producers with in a low-cost, environmental-friendly, practical mitigation technology that can meet all the regulations and requirements in water and air quality.

## Chapter 3: Particulate matter (PM) reduction by Vegetative environmental buffer (VEB): TSP, PM<sub>10</sub>, and PM<sub>2.5</sub>

### Abstract

Particulate matter is a prominent air pollutant associated with poultry houses. Vegetative environmental buffers (VEBs) have been proposed as a sustainable approach to trap particulates close to the source. TSP, PM<sub>10</sub>, and PM<sub>2.5</sub> samples were collected outside a poultry house equipped with a mature VEB during three field campaigns of 5 day and 5 night experiments. The concentration reduction ratios of TSP, PM<sub>10</sub>, and PM<sub>2.5</sub> were calculated using the observed and predicted concentrations. The predicted concentrations were obtained using a modified Gaussian plume model. Particulate matter, especially PM<sub>2.5</sub>, tended to be trapped and accumulated inside the VEB. Comparing the observed and predicted data, the contribution of dispersion and dilution to PM concentration reduction was discerned relative to the contribution of the VEB. The average increase in the reduction of PM ranged from 17% to 25%. TSP and PM<sub>10</sub> concentration reduction ratios were very well correlated, indicating that the PM<sub>10</sub> concentration reduction ratio can be estimated based on TSP data.

### Introduction

Concentrated animal feeding operations (CAFOs), including industrialized modern poultry farms, emit various pollutants, such as particulate matter, ammonia, and odorous gases into the atmosphere (Lacey, Mukhtar, Carey, & Ullman, 2004; Roumeliotis, Dixon, & Van Heyst, 2010). Particulate matter (PM) are categorized as total suspended particle (TSP), particulate matter less or equal to 10 micrometers (PM<sub>10</sub>), and particulate matter less or equal to 2.5 micrometers (PM<sub>2.5</sub>). They are considered a key air pollutant emitted from CAFOs (National

Research Council, 2003).  $PM_{10}$  and  $PM_{2.5}$  are inhalable particles that jeopardize human welfare, animal health, and natural environments, and they are recognized as the criteria air pollutants by the US EPA (US EPA, 2016b).

Research has shown that poultry houses produce  $4.6 - 5.9 \text{ g d}^{-1} \text{ AU}^{-1} PM_{10}$  (Animal Unit = 500 kg) and  $0.8 - 1.4 \text{ g d}^{-1} \text{ AU}^{-1} PM_{2.5}$  at five to six week flock cycles (Roumeliotis, Dixon, & Van Heyst, 2010). Virginia (VA), Maryland (MD), Delaware (DE), and Pennsylvania (PA), which are part of the Mid-Atlantic states of the US, have become one of the major boiler centers due to the growing demand of poultry products from Washington DC to New York. Together the four states supply 9% of the poultry product in the US (USDA National Agricultural Statistics Service, 2017). Consequently, the particulate matter emissions from the poultry industry can have negative effects on the local environment. In 2012, the EPA designated two areas in these states as the nonattainment areas after strengthening the National Ambient Air Quality Standards (NAAQS) for annual  $PM_{2.5}$  concentration to  $12 \mu\text{g}/\text{m}^3$  (US EPA, 2016b).

Different PM remediation technologies for CAFOs have been proposed. Vegetative environmental buffers (VEBs) are a cost-efficient practice that can enhance the aesthetic value of the properties and provide beneficial environment for wildlife (Tyndall & Colletti, 2007). Preliminary studies have indicated that VEBs may also be effective in reducing PM concentrations (Patterson et al., 2008; Patterson & Adrizal, 2005b; Tyndall & Colletti, 2007). VEBs consist of different vegetation, i.e., trees and shrubs, and are installed surrounding or in front of the poultry house emission sources, namely, the ventilation fans. However the efficiency of VEBs in mitigating poultry-emitted PM (TSP,  $PM_{10}$  and  $PM_{2.5}$ ) has not been well characterized since it is challenging to discern the benefits of the VEB versus the effect of distance which causes dilution and dispersion.

The objective of this study is to quantify the emission trends of TSP, PM<sub>10</sub>, and PM<sub>2.5</sub> from a commercial poultry facility using integrated sampling techniques (EPA, 40 CFR Part 53), and to assess the effectiveness of the VEB in reducing PM concentrations. In an effort to assess VEB efficiencies, a modified Gaussian plume model was developed and was used to predict PM concentrations without the presence of a VEB. Model output was then compared with field observation data and the impact of the VEB was determined.

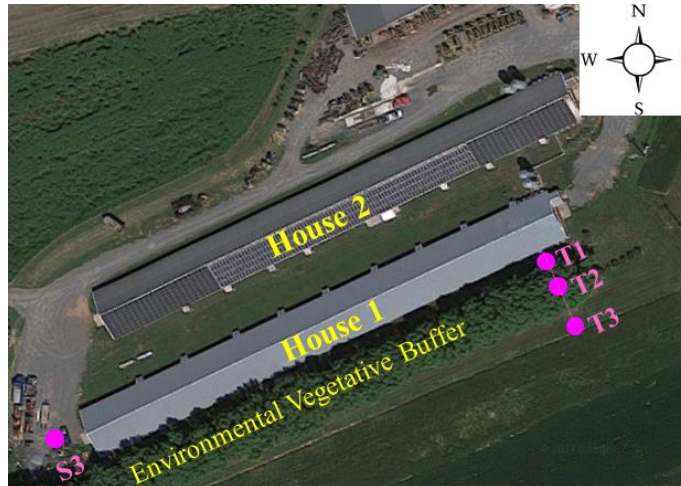
### Materials and methods

#### Site description

A certified organic commercial poultry facility, located in southeastern PA, was selected in this study (**Fig. 1**). Approximately 25,000 free-range chicken were raised with access to fence-in door in two identical poultry houses (152 m length \* 15 m width) for every flock. Litter was removed and the bedding was replaced between flocks. Each house had five 1.2-m tunnel fans on both sides at the end of the tunnel; four 0.9-m sidewall fans (35-m apart) were located on the south sidewall. No sidewall fans were used during the sampling campaigns.

A vegetative environmental buffer (VEB) was located parallel to House 1. This VEB had a row of switch-grass and giant miscanthuses, which were planted in 2012, and a row of hybrid Austere willow trees, which were planted in 2007. The height of the tree and grasses were approximately 10 m and 3 m respectively. The distance between the grass portion of the VEB and the tunnel fans was approximately 5 m.





**Figure 1.** Poultry farm experimental set up map. Three 10-m sampling towers (T1, T2, and T3) were set downwind from the primary tunnel fan of House 1. A 2-m background sampling tower (S3) was set up approximately 150 m away from the tunnel fans.

#### Field sampling campaign set-ups

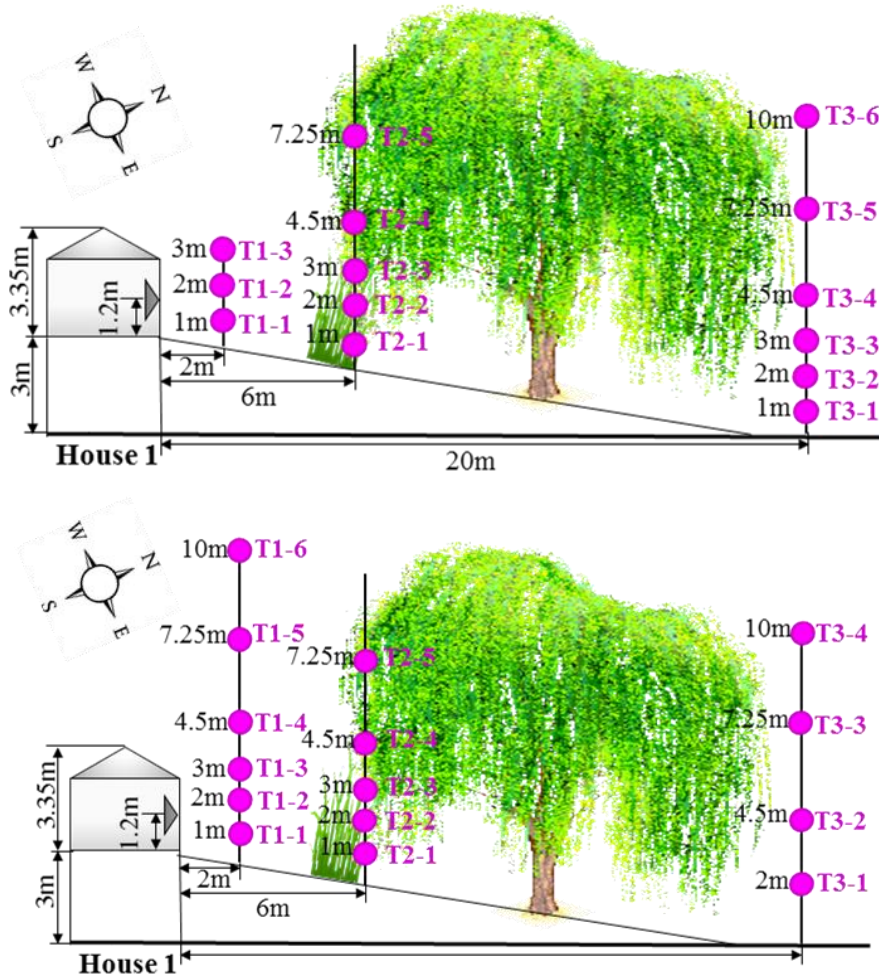
Three sampling campaigns were conducted in July 2014, September 2014 and August 2015 (Campaign 1, 2, and 3). Each campaign held five daytime and 5 nighttime experiments to collect total suspended particulate (TSP) samples over a sampling period around 12 hours.

In Campaign 1 and Campaign 2 (**Fig. 2a**), one 3-m and two 10-m sampling towers with various sampling heights were deployed perpendicularly to the primary tunnel fan of House 1 at distance 2, 6, and 20m. The sampling heights for Tower 1 (T1) were 1, 2, and 3 m; Tower 2 (T2) were 1, 2, 4.5, and 7.25 m; and Tower 3 (T3) were 1, 2, 3, 4.5, 7.25, and 10 m. There was a ground-level elevation drop of about 1 m between T1 and T2 and a drop of about 3 m between T1 and T3. T1-2 was considered as the reference ground-level (2 m). A background sampler (S3) was deployed at approximately 150 m away northwest from the tunnel fans.

In Campaign 3 (**Fig. 2b**), three 10-m sampling towers with various sampling heights were deployed perpendicularly to the primary tunnel fan of House 1 at distance 2, 6, and 20m. The TSP sampling heights for Tower 1 (T1) were 1, 2, 3, 4.5, 7.25, and 10 m; Tower 2 (T2) were 1,

2, 3, 4.5, and 7.25 m; and Tower 3 (T3) were 2, 4.5, 7.25, and 10 m. A background sampler (S3) was deployed at approximately 150 m away northwest from the tunnel fans.

T1-2 was considered as the reference ground-level (2 m). A background sampler (S3) was deployed at approximately 150 m away northwest from the tunnel fans for all the campaigns.



**Figure 2.** PM sampling set-up a) Campaign 1 and Campaign 2; b) Campaign 3. Purple dots represent sampling points.

Meteorological measurements

Meteorological conditions during the sampling period were recorded at each sampling point. Atmospheric pressure was recorded by the 15pisa board mount pressure sensor (TE

Connectivity Corporation, Berwyn, PA); relative humidity was recorded by the HTM2500LF humidity sensor (TE Connectivity Corporation, Berwyn, PA); wind speed and wind direction data were recorded by 034 B wind sensor (Met One Instruments, Inc. Grats Pass, OR). Tower 2 (Fig 3.) was not equipped with a wind sensor due to the field condition limitation. Additional meteorological data was also recorded by a HOBO U30 Station 3.0.0 (Onset Computer Corporation, Bourne, MA).

#### Particulate matter collection and analysis

Total suspended particulate samples were collected using the low-volume TSP sampler heads designed and manufactured by Texas A&M / USDA-ARS (Wanjura, et al. 2005) and Teflon filters. TSP concentrations were obtained using a Mettler MX-5 microbalance (Mettler-Toledo Inc., Columbus, OH) in the environmental chamber. All filters were conditioned in an environmental chamber ( $21 \pm 2$  °C;  $35 \pm 5\%$  RH) for 48 hours prior to gravimetric analyses. PM<sub>10</sub> and PM<sub>2.5</sub> concentrations were obtained by particle size distribution analyses (Beckman Coulter LS230 laser diffraction system, Beckman Coulter Inc., Miami, FL) of the TSP filter samples. All laboratory analyses were conducted at the USDA-ARS Air Quality Lab (AQL) in Lubbock, TX.

#### Gaussian plume model analysis

Most commercially-available dispersion models are designed for vertical air pollutant emissions with relatively large scales ( $> 50$  m), e.g., EPA adopted model: AERMOD, is widely applied on predicting industrial stack and municipal near-road PM emission sources (EPA, 2016a). Poultry house tunnel fans generate horizontal air pollutant emissions, and the sampling distance in this study was less than 50 m. Therefore, a modified small-scale Gaussian plume model (**SI Eq. 1**) (Yang & Yao, 2017) was used in this study to estimate particulate matter

dispersion from a horizontal source. Assumptions underlying this model application can be found at **SI Eq. 1**. Unstable conditions, such as ambient wind speed > 3 m/s and low percentage of the time period under the calm condition (wind speed < 0.3 m/s), can disrupt model performance since Gaussian plume model assumed steady state condition.

This model can provide poultry-emitted PM concentration profiles excluding the VEB influence under the same meteorological conditions as the field sampling period. Hourly averaged metrological data: wind speed, relative humidity, air density, atmospheric pressure, were used for the model calculation. The output of the model was the average PM ratio ( $\frac{Conc.i}{Conc.ref}$ ), where  $Conc.i$  was the PM concentration at a sampling point,  $Conc.ref$  was the PM concentration at T1-2 sampling point (2-m height sampling point at 2 m distance from the tunnel fan, **Fig. 2**). PM predicted concentration was calculated using **Eq. 1**:

$$Model\ Predicted\ Conc. = (Conc.ref - Conc.bg) * \frac{Conc.i}{Conc.ref} + Conc.bg \quad \text{Equation 1}$$

where  $Conc.ref$  was the PM concentration at T1-2,  $Conc.bg$  was the background PM concentration,  $\frac{Conc.i}{Conc.ref}$  was the model generate ratio for each experiment.

Statistical analysis

Ground-level was defined as the 2 m height at T1. VEB reduction (reduction rate) was calculated using **Eq. 2**:

$$collection\ eff. = (1 - \frac{Conc.i - Conc.ref}{Conc.ref}) \times 100\% \quad \text{Equation 2}$$

where  $Conc.i$  was the ground-level pollutant concentration at T2 or T3: T2-3 T3-4 sampling points were used for Campaign 1 and Campaign 2 (**Fig. 2a**), T2-3 and T3-2 were used for Campaign 3 (**Fig. 2b**),  $Conc.ref$  was the ground-level pollutant concentration at T1 (T1-2, **Fig. 2**) for all the campaigns.

All statistical analyses, including one-way ANOVA, correlation matrix (Pearson correlation), t-test, and standard variance, were performed by GraphPad Prism 7.03 (GraphPad Software, Inc. La Jolla, CA) and Microsoft Excel. Tukey boxplots were used to analyze pollutant concentrations, where each boxplot represented the quartile range of 25<sup>th</sup> percentile (lower) to 75<sup>th</sup> percentile (upper), whiskers: 75<sup>th</sup> percentile plus 1.5 times of inter-quartile range or the maximum data value, and 25<sup>th</sup> percentile minus 1.5 times of inter-quartile range or the minimum data value. The individual points plotted beyond the whiskers of the box-and-whiskers plots were outliers.

### Results and discussion

#### Meteorological conditions

Microclimatic conditions were recorded at each sampling point during every sampling period. The microclimate can be influenced by the heat emitted from the poultry house through the tunnel fan to the VEB. The average temperature, atmospheric pressure, relative humidity, and wind speed of five day/night experiments from each campaign are presented in **Table 1**. Ambient wind speed and calm condition percentage were also reported and were based on the background meteorological data.

**Table 1.** Average diurnal and nocturnal meteorological condition<sup>a</sup>

	Temperature (°C)		Pressure (kPa)		Relative Humidity (%)		Wind Speed (m/s)		Ambient Wind Speed (m/s)		Calm % <sup>b</sup>	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
Camp 1	27.7 (2.1)	22.4 (2.0)	91.6 (1.8)	94.9 (0.9)	57.2 (6.2)	67.9 (5.9)	2.3 (0.5)	1.9 (0.6)	1.1 (0.28)	0.4 (0.17)	28% (11%)	88% (20%)
Camp 2	24.7 (2.0)	20.6 (1.8)	94.2 (1.3)	96.3 (0.9)	65.1 (6.2)	74.3 (4.5)	1.9 (0.4)	1.4 (0.4)	1.5 (0.33)	0.9 (0.46)	33% (8%)	43% (30%)
Camp 3	25.6 (2.7)	21.3 (2.3)	94.2 (1.3)	96.3 (0.9)	68.7 (8.2)	78.7 (8.2)	1.0 (0.4)	0.9 (0.4)	1.5 (0.26)	0.4 (0.19)	26% (7%)	68% (35%)

<sup>a</sup> Values reported as average values of meteorological conditions of five day/night field sampling period, and the standard deviations are in parentheses below the value.

<sup>b</sup> Percentage of the time period under the calm condition (wind speed < 0.3 m/s) during an experimental sampling period.

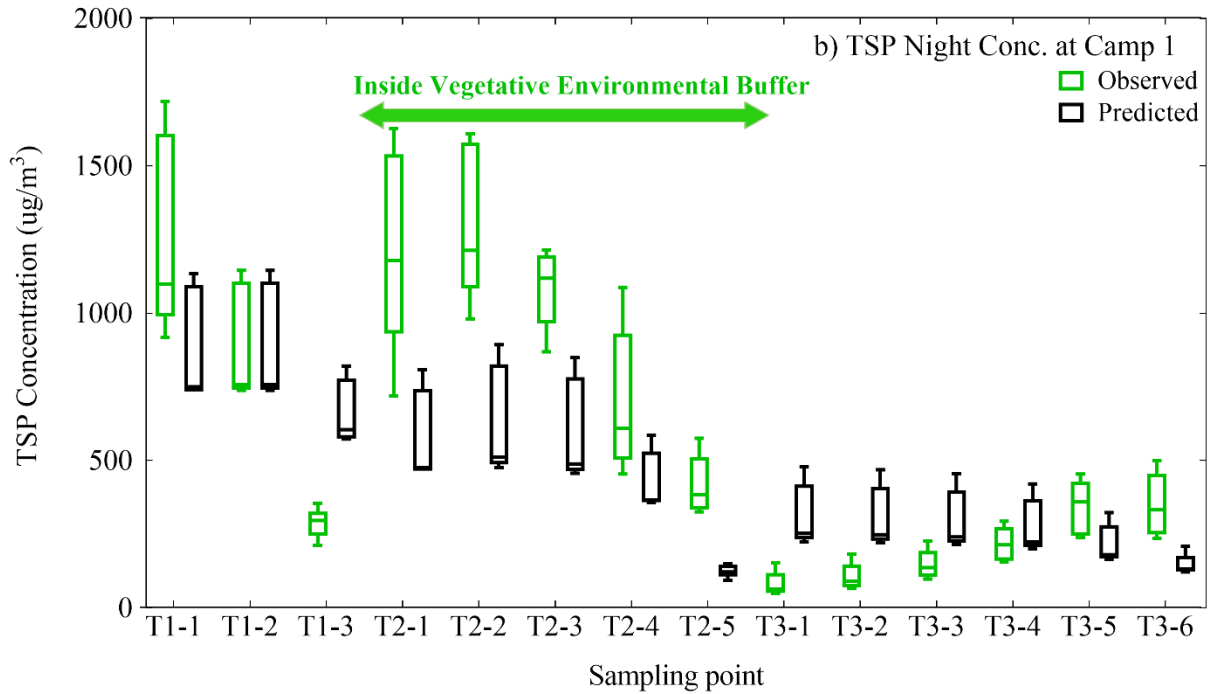
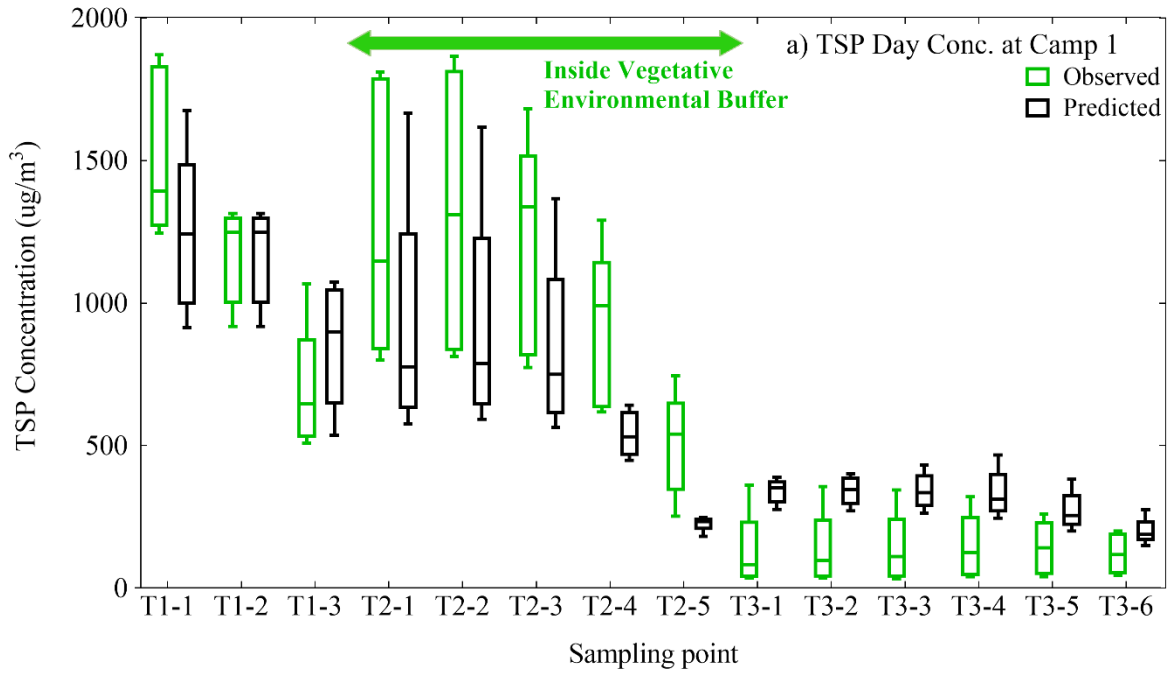
## PM concentrations

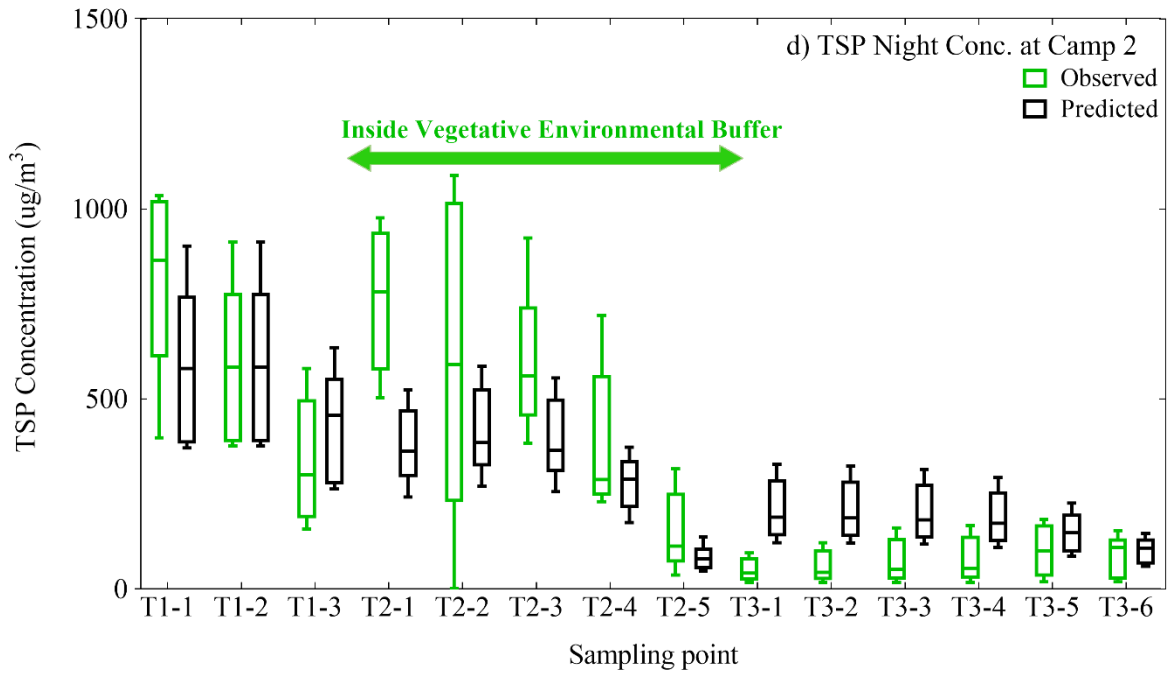
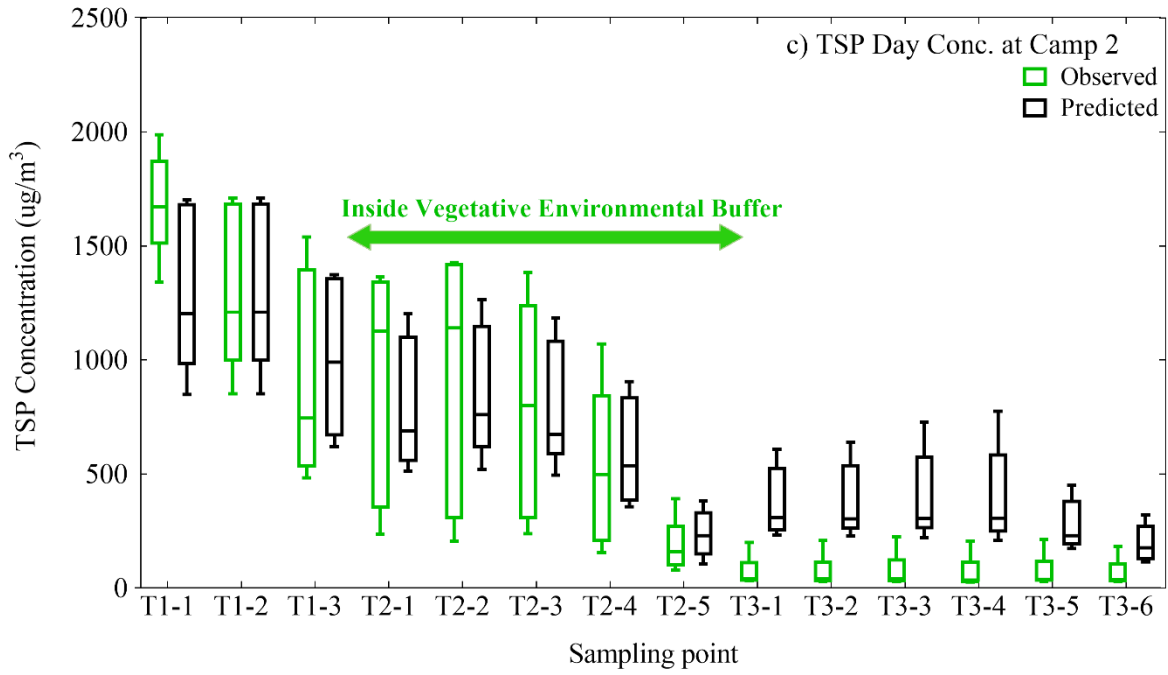
Each field campaign provided five sets of both diurnal and nocturnal particulate matter concentration profiles. Based on statistical analysis (one-way ANOVA and paired t-test), the diurnal and nocturnal TSP measurements for Campaign 1 showed no statistical significant difference ( $p$ -value  $> 0.05$ ), but measurements for Campaigns 2 and 3 were significantly different ( $p$ -value  $< 0.05$ ). The diurnal and nocturnal PM<sub>10</sub> measurements were also significantly different in all the campaigns ( $p$ -value  $< 0.05$ ). However, the diurnal and nocturnal PM<sub>2.5</sub> measurements were only significantly different for Campaign 1 ( $p$ -value  $< 0.05$ ). Therefore, day time and night time PM emissions were analyzed separately. PM concentrations from each experiment can be found in **SI Table 2, 3, and 5**.

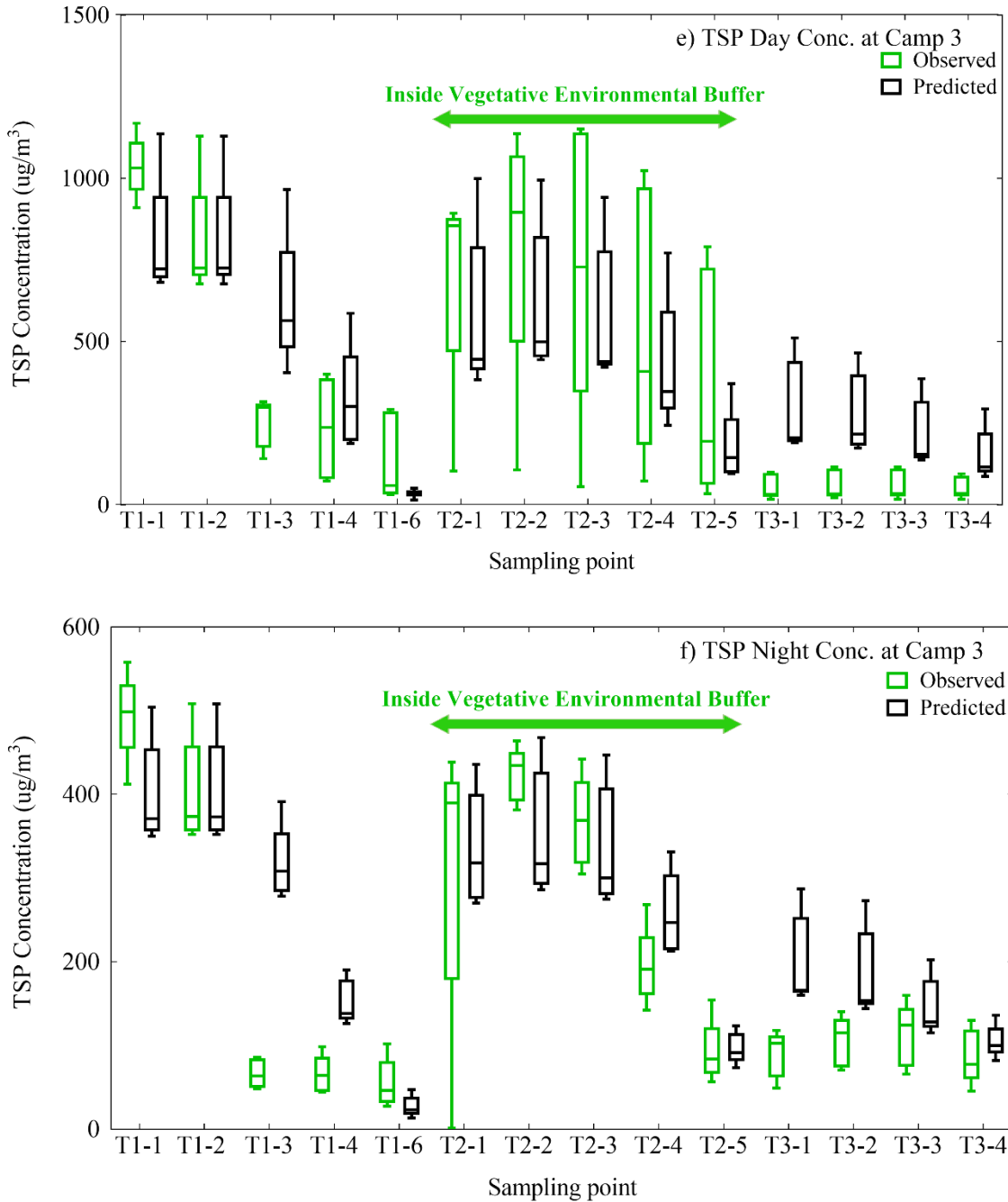
Diurnal and nocturnal observed and predicted TSP concentrations were plotted at each sampling point for all three campaigns (**Fig. 3**). Very similar trends were observed for PM<sub>10</sub> and PM<sub>2.5</sub> concentrations (**SI Fig 4, SI Fig. 5**). For all campaigns, the observed and predicted TSP concentrations at T1 decreased with increasing height, particularly in Campaign 3 which had higher samplers at T1. This result was expected because the tunnel fan was at approximately 2 m in height. T1 was 2 m away from the tunnel fan. Particulate matter cannot disperse to the higher samplers ( $> 3$  m) within this short distance. The model also tended to over-estimate TSP concentrations at the higher sampling points on T1 due to the limitation the model (Yang & Yao, 2017). A similar trend was observed for TSP concentrations at T2 which is located inside the VEB. Ground-level observed TSP concentrations at T2 were all larger than the predicted concentrations. This may indicate that the TSP was accumulating in between the grass and the tree rows of the VEB.

Ground level observed TSP concentration was significantly lower ( $p$ -value  $< 0.05$ ) behind the VEB (T3) than in front of the tunnel fan (T1). For the nocturnal experiments, a slight increase in TSP concentrations was observed as the height increased at T3 (**Fig. 3b, 3d, and 3f**). However, diurnal TSP concentrations were essentially the same at different heights of T3 (**Fig. 3a, 3c, and 3e**). Ground-level observed concentration at T3 were all noticeably lower than predicted data. Since the predicted data was only under the influence of dispersion, while both dispersion and VEB were affecting observed PM concentrations, this result revealed the promising potential of VEB in further reducing PM emissions from the poultry houses.









**Figure 3.** Tukey box-plots of observed and predicted TSP concentrations at different sampling points. The boxplot represents the quartile range of the 25<sup>th</sup> percentile (lower) to the 75<sup>th</sup> percentile (upper). The whiskers are the 75<sup>th</sup> percentile plus 1.5 times of inter-quartile range or the maximum data value and the 25<sup>th</sup> percentile minus 1.5 times of inter-quartile range or the minimum data value. Observed TSP concentrations are shown in green and were from the five daytime or nighttime sampling experiments of each campaign. Predicted TSP concentrations are

shown in black and were from model calculations with the same meteorological conditions as the same sampling period. a) Diurnal observed and predicted TSP concentrations at Campaign 1; b) Nocturnal observed and predicted TSP concentrations at Campaign 1; c) Diurnal observed and predicted TSP concentrations at Campaign 2; d) Nocturnal observed and predicted TSP concentrations at Campaign 2; e) Diurnal observed and predicted TSP concentrations at Campaign 3; and f) Nocturnal observed and predicted TSP concentrations at Campaign 3. Sampling points were shown in the **Fig. 2**. Tower 1 was 2 m away from the tunnel fan; Tower 2 was inside the VEB and was 6 m away from the tunnel fan; Tower 3 was behind the VEB and was 20 m away from the tunnel fan.

Correlation between TSP, PM<sub>10</sub>, PM<sub>2.5</sub> concentrations and meteorological factors

Meteorological conditions were expected to affect particulate matter concentrations. **Table 2** and **Table 3** showed the correlations between PM (TSP, PM<sub>10</sub> and PM<sub>2.5</sub>) concentrations and the sampling meteorological conditions. As expected, PM<sub>10</sub> and PM<sub>2.5</sub> were closely correlated to TSP. Temperature and wind speed were both positively correlated to PM concentrations. Higher temperature resulted in larger PM emission due to the higher demand for the tunnel fan ventilation to maintain the temperature inside the poultry house. Higher wind speed contributed to PM dispersion, which is consistent with earlier LiDAR studies (Willis et al. 2017a, 2017b). Furthermore, PM concentrations were negatively correlated with distance as expected. Atmospheric pressure, height, and relative humidity were not correlated to PM concentrations.

**Table 2.** Pearson correlation matrix between diurnal PM (TSP, PM<sub>10</sub> and PM<sub>2.5</sub>) emissions and the meteorological factors of temperature (T), atmospheric pressure (P), relative humidity (RH), wind speed (WS), sampling heights, and the distance to the tunnel fan.

	T	P	RH	WS	Height	Distance	PM <sub>10</sub>	PM <sub>2.5</sub>
TSP	0.51	-0.01	-0.15	0.38	-0.11	-0.69	0.95	0.68
PM <sub>10</sub>	0.56	-0.11	-0.29	0.46	-0.16	-0.59		0.72
PM <sub>2.5</sub>	0.34	-0.17	-0.35	0.33	-0.19	-0.30	0.72	

**Table 3.** Pearson correlation matrix between nocturnal PM (TSP, PM<sub>10</sub> and PM<sub>2.5</sub>) emissions and the meteorological factors of temperature (T), atmospheric pressure (P), relative humidity (RH), wind speed (WS), sampling heights, and the distance to the tunnel fan.

	T	P	RH	WS	Height	Distance	PM <sub>10</sub>	PM <sub>2.5</sub>
TSP	0.34	-0.24	-0.10	0.55	-0.21	-0.50	0.86	0.78
PM <sub>10</sub>	0.13	-0.14	-0.20	0.59	-0.25	-0.38		0.76
PM <sub>2.5</sub>	0.07	-0.07	-0.11	0.33	-0.20	-0.26	0.76	

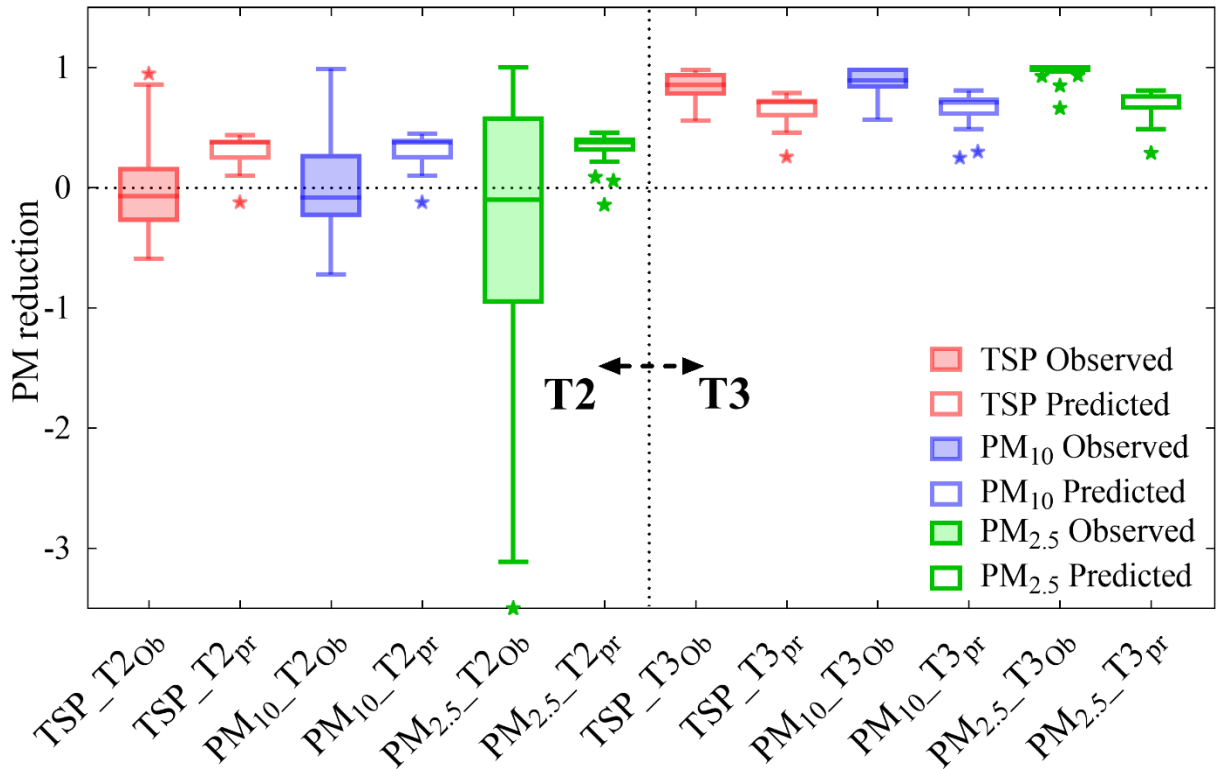
#### Ground-level PM concentration reduction

Diurnal and nocturnal PM (TSP, PM<sub>10</sub> and PM<sub>2.5</sub>) concentration reduction ratios were not significantly different ( $p$ -value > 0.05), nor were there significant differences between campaigns ( $p$ -value > 0.05). Therefore, all the reduction data for each PM type were combined for analyses.

The observed ground-level TSP, PM<sub>10</sub> and PM<sub>2.5</sub> concentration reduction ratios at T2 were lower than the corresponding predicted ratios (**Fig. 4**). The median observed PM concentration reduction ratios were negative. In addition, the averaged observed ground-level VEB reduction inside the buffer for TSP, PM<sub>10</sub> and PM<sub>2.5</sub> were  $-2\% \pm 40\%$ ,  $1\% \pm 43\%$ , and  $-25\% \pm 119\%$ , respectively, which were lower than predicted values:  $31\% \pm 13\%$ ,  $31\% \pm 13\%$ , and  $34\% \pm 14\%$ , respectively. These data suggest that the particles were accumulating between the grass row and the tree row of the VEB.

The observed ground-level TSP, PM<sub>10</sub> and PM<sub>2.5</sub> concentration reduction ratios at T3, which is behind the VEB, were higher than predicted reduction. Behind the buffer, the averaged observed ground-level TSP, PM<sub>10</sub> and PM<sub>2.5</sub> concentration reduction ratios were  $84\% \pm 13\%$ ,  $88\% \pm 12\%$ , and  $97\% \pm 8\%$ , respectively, which were significantly larger ( $p$ -value < 0.0001) than the predicted values:  $67\% \pm 12\%$ ,  $67\% \pm 13\%$ , and  $70\% \pm 13\%$ , respectively. The reduction

difference demonstrated the VEB effectiveness in reducing the PM emissions from the poultry house. The model helped to isolate the effects of dispersion and dilution from the effects of the VEB in reducing PM concentrations. The result showed the VEB increased the reduction of TSP, PM<sub>10</sub> and PM<sub>2.5</sub> by 17%, 21%, and 25% in average, respectively.

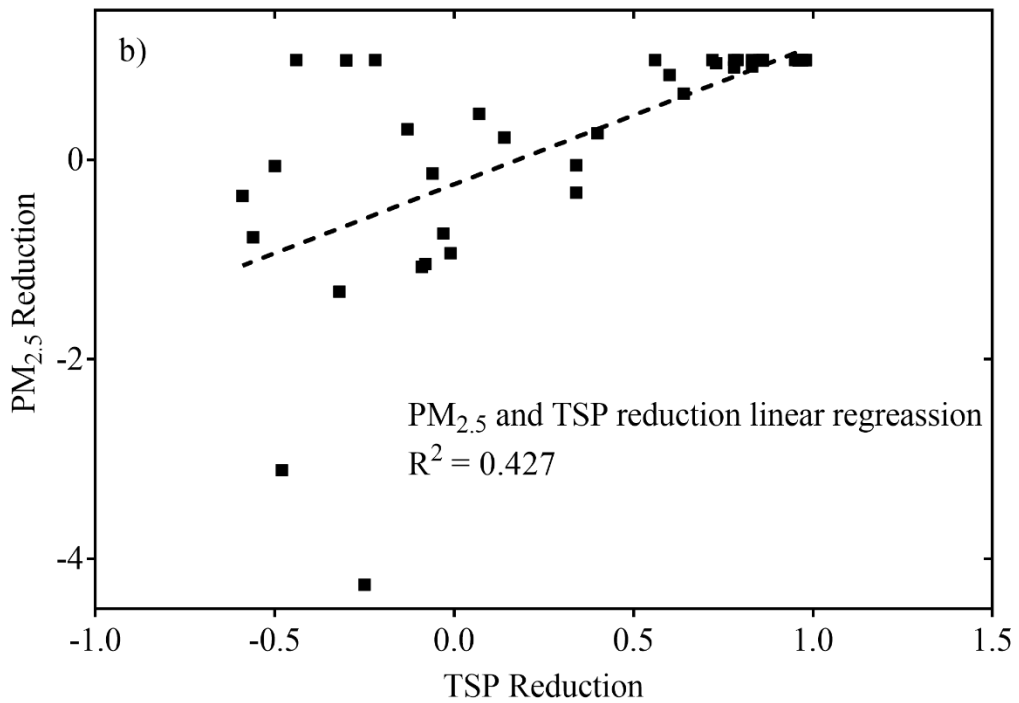
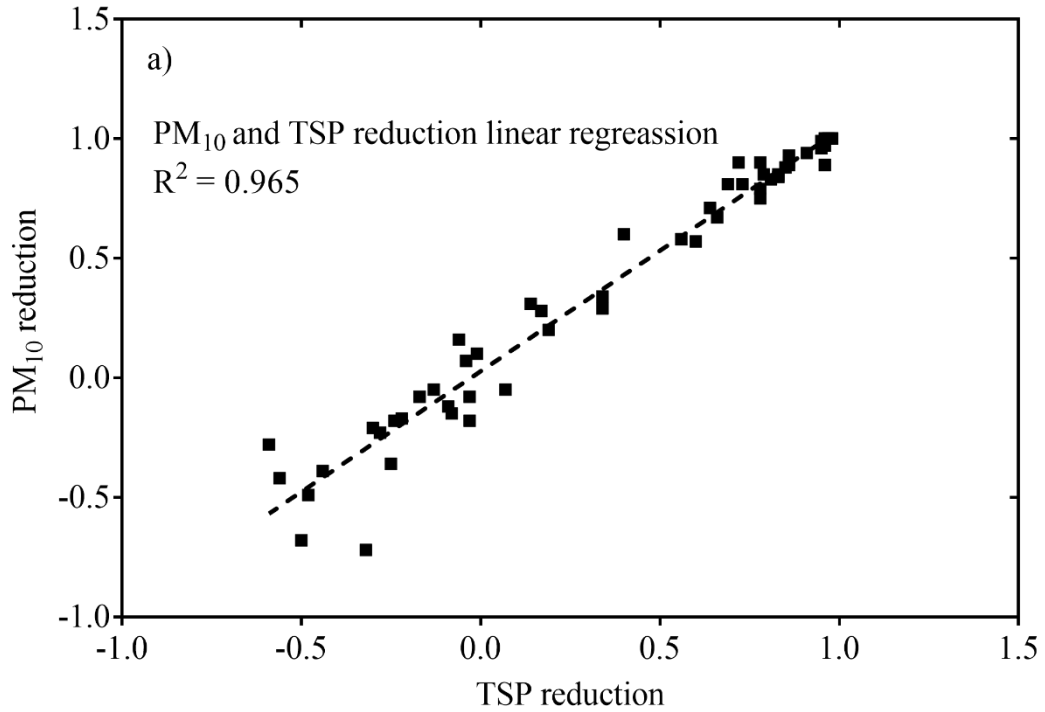


**Figure 4.** Tukey box-plots of observed and predicted PM concentration reduction ratios at T2 (left side) and T3 (right side). The boxplot represents the quartile range of the 25<sup>th</sup> percentile (lower) to the 75<sup>th</sup> percentile (upper). The whiskers are the 75<sup>th</sup> percentile plus 1.5 times of inter-quartile range or the maximum data value and the 25<sup>th</sup> percentile minus 1.5 times of inter-quartile range or the minimum data value. The observed PM concentration reduction ratios are represented in solid-boxes and were from the 30 sampling experiments. The predicted PM concentration reduction ratios are shown in open-boxes and were from model calculations with the same meteorological conditions as the same sampling period.

### Correlation between ground-level PM concentration reduction ratios and metrological factors

A linear regression was conducted between TSP and PM<sub>10</sub> concentration reduction ratios and a very strong correlation was found ( $R^2 = 0.97$ , **Fig. 5a**). The result showed the possibility of using TSP concentration reduction ratios to estimate PM<sub>10</sub> concentration reduction ratios, which is important since TSP samples are much easier to collect and analyze. However, only a weak correlation between TSP and PM<sub>2.5</sub> concentration reduction ratios was observed ( $R^2 = 0.43$ , **Fig. 5b**). This could be due to the very low contribution of PM<sub>2.5</sub> to TSP relative to the contribution of PM<sub>10</sub>.





**Figure 5.** Linear regression plots between a) PM<sub>10</sub> and TSP concentration reduction ratios,  $PM_{10} = 1.01 \text{ TSP} + 0.027$ ,  $R^2 = 0.97$ ; b) PM<sub>2.5</sub> and TSP concentration reduction ratios,  $PM_{2.5} = 1.38 \text{ TSP} - 0.24$ ,  $R^2 = 0.43$ . The dotted lines are the best-fit regression lines.

As expected, strong positive correlations were found between ground-level TSP, PM<sub>10</sub> and PM<sub>2.5</sub> concentration reduction ratios, especially between TSP and PM<sub>10</sub> (**Table 4**). Distance was also positively correlated to the PM concentration reduction ratios due to the effects of dispersion and dilution. No significant correlation between PM concentration reduction ratios and meteorological conditions were observed.

**Table 4.** Pearson correlation matrix for ground-level TSP, PM<sub>10</sub> and PM<sub>2.5</sub> concentration reduction ratios with the corresponding meteorological factors of temperature (T), atmospheric pressure (P), relative humidity (RH), wind speed (WS), and sampling distance to the tunnel fan.

	T	P	RH	WS	Distance	PM <sub>10</sub>	PM <sub>2.5</sub>
TSP	-0.05	0.10	0.04	0.03	0.83	0.98	0.65
PM <sub>10</sub>	-0.02	0.06	0.02	0.05	0.82		0.69
PM <sub>2.5</sub>	0.08	-0.07	-0.16	0.17	0.59	0.69	

### Conclusions

This study demonstrated that the VEB can reduce poultry-emitted particulate matter concentrations. Although dispersion and dilution contribute to the overall reduction of PM concentrations, this study showed that the VEB increases the reduction of ground-level TSP, PM<sub>10</sub> and PM<sub>2.5</sub> by 17%, 21%, and 25%, respectively. In addition, PM tended to accumulate inside the buffer rows. TSP, PM<sub>2.5</sub> and PM<sub>10</sub> concentration trends and meteorological conditions (temperature and wind speed) were statistically correlated. Higher temperature caused increased house ventilation which increased PM concentrations. Stronger wind speed also contributed to PM dispersion. TSP, PM<sub>2.5</sub> and PM<sub>10</sub> concentration reduction by VEBs were very well statistically correlated. Based on linear regression analysis, PM<sub>10</sub> concentration reduction can be predicted from TSP concentration reduction data.

## Chapter 4: Assessment of Vegetative Environmental Buffer (VEB) to mitigate poultry-emitted ammonia and PM<sub>2.5</sub>

### Abstract

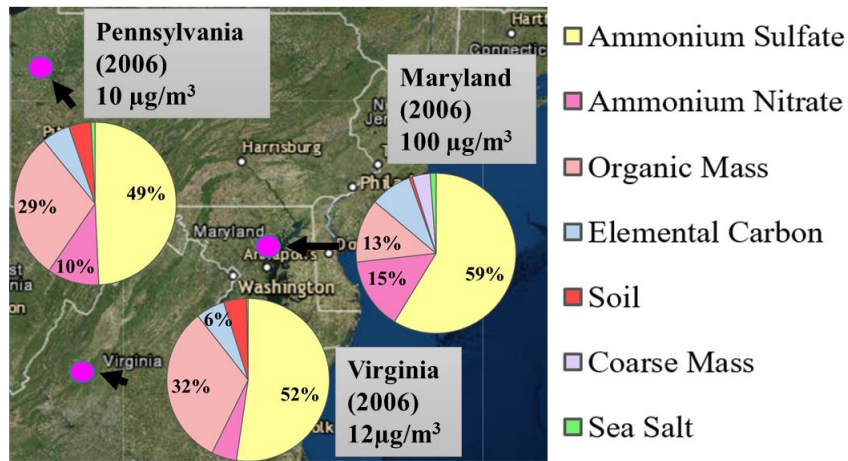
Ammonia emitted from concentration animal feeding operations (CAFOs), such as industrialized poultry houses, has become a concern globally. Vegetative environmental buffers (VEBs) have been introduced to the poultry industry as an inexpensive practice that provide a visual screen for the facilities. Preliminary studies indicated that VEBs may also reduce NH<sub>3</sub> and PM<sub>2.5</sub> emitted from the poultry houses. Few studies have been conducted to evaluate the effectiveness of a functioning VEB in trapping NH<sub>3</sub> and PM<sub>2.5</sub>. In this study, three field sampling campaigns were conducted at a VEB-equipped poultry farm to collect NH<sub>3</sub> and PM<sub>2.5</sub> samples downwind from the ventilation fans. A modified Gaussian Plume model was used to estimate NH<sub>3</sub> and PM<sub>2.5</sub> concentrations without a VEB under the same meteorological conditions as the sampling period. The results revealed that the VEB promoted the reduction of PM<sub>2.5</sub> by 20% to 30%, and NH<sub>3</sub> by 13% to 25%. PM<sub>2.5</sub> reduction was closely correlated to NH<sub>3</sub> reduction.

### Introduction

Agricultural activities are the largest contributors of ammonia in the atmosphere. Domestic animals, mostly raised under the concentrated animal feeding operations (CAFOs), contribute to almost half of the total ammonia emissions globally in 1990 (Bouwman et al., 1997). In the US, CAFOs have contributed approximately  $2.2 \times 10^9$  kg NH<sub>3</sub>/year in 2010 of which 27% was from poultry houses. In 2030, poultry operations are predicted to emit nearly 33% of total CAFO-emitted ammonia of  $2.4 \times 10^9$  kg NH<sub>3</sub>/year. The poultry industry has the highest yearly ammonia emission rate among the U.S. CAFOs (EPA, 2004).

Ammonia (NH<sub>3</sub>) emission from CAFOs, including industrialized poultry houses, is a concern due to the potential negative effects on the ecosystems and human health. Inhaling low-concentration gaseous NH<sub>3</sub> can cause respiratory irritations, and high-concentration exposure can result in more severe problems (ATSDR, 2011). Through both wet and dry deposition processes, NH<sub>3</sub> can impact ecological balances by influencing soil and stream acidity as well as soil and coastal productivity and alter biodiversity in the ecosystems. For example, due to high ambient nitrogen deposition, heathlands in western Europe have been transformed and are now dominated by grass species. More than 35% of Dutch heathland has become grassland (WHO Regional Office for Europe, 2000). Studies have also shown the NH<sub>3</sub> accumulation in the environment can lead to acidification, eutrophication, photo chemical air pollution, and ecosystem fertilization (Galloway et al., 2003; Paerl, 1995). In the Netherlands, research has shown that a decline or even disappearance of macrophyte communities as a result of plankton bloom caused by eutrophication of the water and the sediment (Roelofs, 1983).

Ammonia is also a well-known secondary precursor of fine particles (particulate matter aerodynamic diameter  $\leq 2.5 \mu\text{m}$ , PM<sub>2.5</sub>) mostly in the form of ammonium sulfate and ammonium nitrate. PM<sub>2.5</sub> can cause breathing problems and reduce visibility, and it is regulated by US EPA as a criteria air pollutant (EPA, 2016b). Secondarily formed PM<sub>2.5</sub> is typically derived via rapid chemical reactions between ammonia, sulfur dioxide (SO<sub>2</sub>), and nitrogen oxides (NO<sub>x</sub>) in the presence of water. In the eastern North America, approximately 50% of secondary PM<sub>2.5</sub> has inorganic speciation composed of ammonium, nitrate, and sulfate (Erisman & Schaap, 2004; McMurry et al., 2004). **Fig. 1** shows the composition and annual average concentration of PM<sub>2.5</sub> at selected monitoring sites in the Mid-Atlantic rural areas of the eastern US (EPA, 2016c). The dominant components of PM<sub>2.5</sub> in this region were ammonium sulfate and ammonium nitrate.



**Figure 1.** Composition of PM<sub>2.5</sub> at representative Mid-Atlantic rural areas in 2006. Averaging period and average PM<sub>2.5</sub> concentration are indicated under the location. Purple dots represent the Interagency Monitoring of Protected Visual Environments (IMPROVE) sampling sites (EPA, 2016c).

Industrialization of modern poultry farms has been expanding in the Mid-Atlantic States due to the large demand for poultry products in the areas. Virginia (VA), Maryland (MD), Delaware (DE), and Pennsylvania (PA) alone supply 9% of the poultry product in the US (USDA National Agricultural Statistics Service, 2017). Concomitantly, ammonia is one of the top three chemicals released into the air in these four states (EPA, 2015b), and four of the nine PM<sub>2.5</sub> nonattainment and maintenance areas designated by EPA are in this region (EPA, 2012). Thus, although previous research interests were limited to the air quality issues inside the poultry houses, research efforts have been expanded to assessing the ammonia and PM<sub>2.5</sub> emissions from poultry houses and to the development of mitigation technologies. Innovative remediation technologies, including filtration, electrostatic precipitators, and acid scrubbers require frequent maintenance and sufficient energy that can be costly, while vegetative environmental buffers (VEBs) are considered as a more economical practice (Ullman, Mukhtar, Lacey, & Carey, 2004).

VEBs have been introduced to the poultry industry as a cost-efficient air pollutant entrapment practice. VEBs are rows of vegetation planted near the poultry houses and may help

to reduce the nuisance complaints of neighbors near the farms and provide a more appealing neighborhood environment (Patterson et al., 2008). Studies have shown that poplar, hybrid willow, and Streamco willow in Pennsylvania areas are preferable choices for efficiently trapping ammonia and particulate matter emitted from the poultry houses (Adrizar et al., 2008).

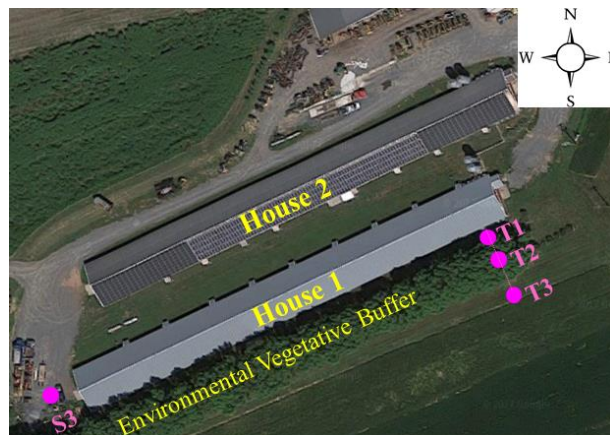
Early studies reported that VEBs have potential in trapping air pollutants emitted from the CAFOs. A VEB with 6 – 12 m height can benefit in air pollutant plume interception, disruption and dilution since most CAFO air pollutant sources are at ground level and the tendency of the air pollutant plume travels along the ground (Hernandez, Trabue, Sauer, Pfeiffer, & Tyndall, 2012; Tyndall & Colletti, 2007). It has also been shown that the foliar nitrogen in VEB plants near the tunnel fan was higher than those that were further away (Parker, Malone, & Walter, 2012; Tyndall & Colletti, 2007). However, the effectiveness of VEBs in mitigating poultry-emitted air pollutants apart from dilution or dispersion has not been examined. In addition, little research has been conducted concerning the relationship between poultry-emitted  $\text{NH}_3$  and  $\text{PM}_{2.5}$ .

The objective of this study is to develop appropriate methodology to evaluate the efficacy of VEB in reducing  $\text{NH}_3$  and  $\text{PM}_{2.5}$  emitted from poultry houses, as well as assess the possible correlations between  $\text{NH}_3$  and  $\text{PM}_{2.5}$  emitted concentrations and the reduction of these concentrations. A VEB-equipped commercial farm was identified for  $\text{NH}_3$  and  $\text{PM}_{2.5}$  field sample collection. A modified small-scale Gaussian plume model was then used to calculate the  $\text{NH}_3$  and  $\text{PM}_{2.5}$  concentration profiles with no VEB present under the same meteorological conditions as the field sampling period to obtain predicted data. These predictions were then compared with the field data to discern the contribution of the VEB in decreasing the concentrations versus the decrease from dilution of the plume as a function of distance.

## Materials and methods

### Site description

A certified organic commercial poultry facility located in southeastern PA was selected for intensified ammonia and particulate matter sampling Campaign (**Fig. 2**). This farm produced free-range chicken with access to fence-in door and consists of two identical poultry houses (152 m length \* 15 m width); each held approximately 25,000 chicken per flock. Litter was removed and the bedding was replaced between each flock. Each house had five 1.2-m tunnel fans on both sides at the tunnel end; four 0.9-m sidewall fans (35-m apart) were located on the south sidewall. No sidewall fans were used during the field Campaign. A vegetative environmental buffer (VEB) was located parallel to the first house (House 1). This VEB had a row of switch-grass and giant miscanthuses, which were planted in 2012, and a row of hybrid Austere willow trees, which were planted in 2007. The height of the tree and grasses were approximately 10 m and 3 m respectively. The distance between the grass portion of the VEB and the tunnel fans was approximately 5 m.



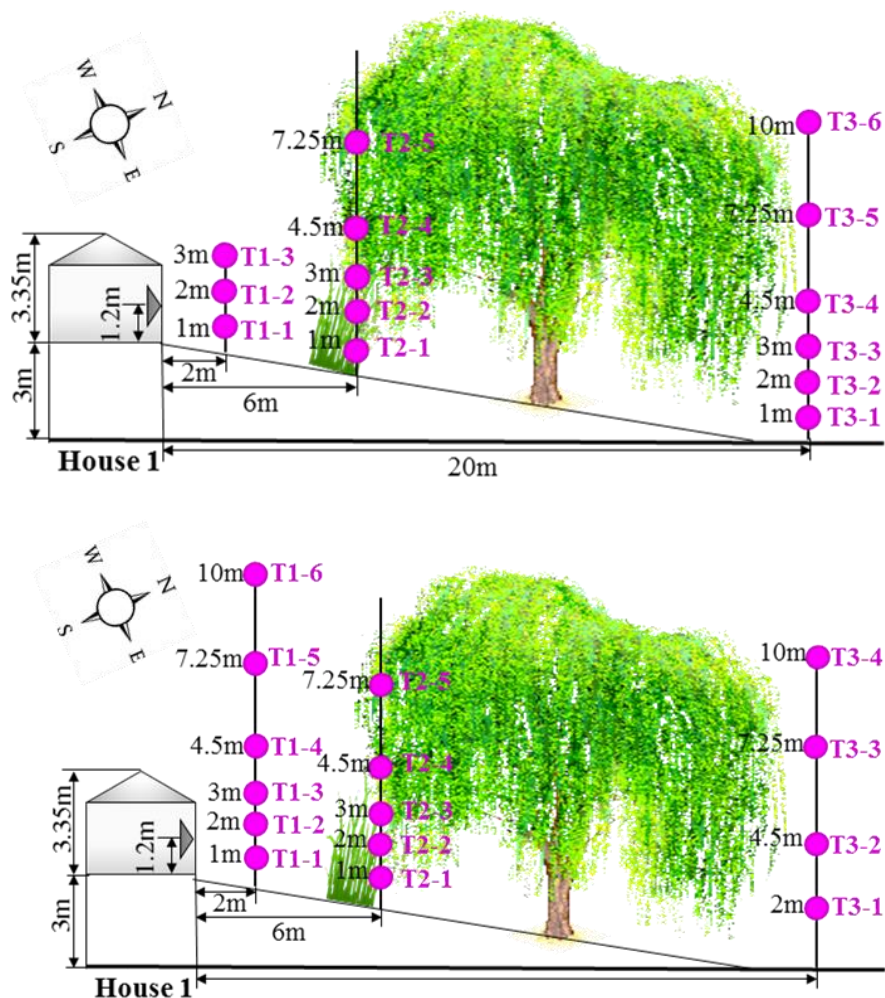
**Figure 2.** Poultry farm experimental set up image. Three 10-m sampling towers (T1, T2, and T3) were set downwind from the primary tunnel fan of House 1. A 2-m background sampling tower (S3) was set up approximately 150 m away from the tunnel fans.

### Field sampling campaign set-ups

Three field sampling Campaign were conducted in July, September 2014 and August 2015 (Campaign 1, 2, and 3). Each Campaign held five daytime and 5 nighttime experiments to collect total suspended particulate (TSP) and NH<sub>3</sub> samples over a sampling period around 12 hours. In Campaign 1 (**Fig. 3a**), one 3-m and two 10-m sampling towers with various sampling heights were deployed for both TSP and NH<sub>3</sub> samplers perpendicularly to the primary tunnel fan of House 1 at distance 2, 6, and 20m. The sampling heights for Tower 1 (T1) were 1, 2, and 3 m; Tower 2 (T2) were 1, 2, 4.5, and 7.25 m; and Tower 3 (T3) were 1, 2, 3, 4.5, 7.25, and 10 m. There was a ground-level elevation drop of about 1 m between T1 and T2 and a drop of about 3 m between T1 and T3. A background sampler (S3) was deployed at approximately 150 m away northwest from the tunnel fans. In Campaign 2 (**Fig. 3a**), the same set up as Campaign 1 was used. In Campaign 3 (**Fig. 3b**), three 10-m sampling towers with various sampling heights were deployed for both TSP and NH<sub>3</sub> samplers perpendicularly to the primary tunnel fan of House 1 at distance 2, 6, and 20m. The PM sampling height for Tower 1 (T1) were 1, 2, 3, 4.5, 7.25, and 10 m; Tower 2 (T2) were 1, 2, 3, 4.5, and 7.25 m; and Tower 3 (T3) were 2, 4.5, 7.25, and 10 m. The NH<sub>3</sub> sampling height for Tower 1 (T1) were 1, 2, 4.5, 7.25, and 10 m; Tower 2 (T2) were 1, 2, 4.5, and 7.25 m; and Tower 3 (T3) were 2, 4.5, 7.25, and 10 m. A background sampler (S3)



was deployed at approximately 150 m away northwest from the tunnel fans.



**Figure 3.** Field sampling set-up, purple dots represent sampling locations. a) TSP and NH<sub>3</sub> sampler locations in Campaign 1 and Campaign 2; b) TSP (all the sampling points) and NH<sub>3</sub> (no T1-3, T2-3) samplers locations in Campaign 3.

#### Meteorological measurements

Meteorological recording devices were installed at each of the sampling points to record the weather conditions during the sampling period: atmospheric pressure was recorded by the 15pisa board mount pressure sensor (TE Connectivity Corporation, Berwyn, PA), and relative humidity was recorded by the HTM2500LF humidity sensor ((TE Connectivity Corporation, Berwyn, PA)). Wind speed and wind direction data were recorded by 034 B wind sensor (Met

One Instruments, Inc. Grats Pass, OR) at every sampling point except the ones on T2 (**Fig. 2**). Additional meteorological measurements (temperature, pressure, relative humidity, wind speed, and wind direction) had also been recorded by a HOBO U30 Station 3.0.0 (Onset Computer Corporation, Bourne, MA).

#### Particulate matter sampling and analysis

TSP was collected using a Teflon filters coupled with low-volume TSP sampler heads designed and manufactured by Texas A&M / USDA-ARS (Wanjura, et al. 2005). Filter sample was preserved in individual petri dish sealed by electric tape. All the samples were packed and delivered to the USDA-ARS Air Quality Lab in Lubbock, TX, where the PM laboratory analyses were conducted. A Beckman Coulter LS230 laser diffraction system (Beckman Coulter Inc., Miami, FL) with software version 3.29 was used to perform the particle size distribution analyses (PSD) on TSP samplers to obtain the mass fraction of PM with diameter less than or equal to 2.5  $\mu\text{m}$  ( $\text{PM}_{2.5}$ ).

#### Ammonia sampling and analysis

Passive diffusive samplers (Radiello, Sigma-Aldrich Co. LLC. Darmstadt, Germany) were deployed to measure the time-averaged ammonia concentrations. Radiello sampler used microporous polyethylene impregnated with phosphoric acid as cartridges to adsorb ammonia. Only the gaseous-phase ammonia were absorbed due to the diffusive layer of Radiello, which functioned as a shield to eliminate any interferences from particulate matters. Cartridge sample was preserved in sealed individual Radiello tube. All the samples were packed and brought back to the laboratory. All Samplers were quantified by UV/Visible-1800 spectrometry (Shimadzu Corp. Kyoto, Japan) at wavelength  $\lambda = 635 \text{ nm}$  as indophenol (Radiello, 2006).

## Gaussian plume model analysis

Most poultry available commercial dispersion models were designed for vertical air pollutant concentration prediction with relatively large scales (>50 m). Poultry house tunnel fans generated horizontal air pollutant emissions, and the sampling distance in this study was much less than 50 m. Therefore, a modified small-scale Gaussian plume model (**SI Eq. 1**) (Yang & Yao, 2017) as used in this study to estimate particulate matter dispersion from a horizontal source. Assumptions underlying this model application can be found at **SI Eq. 1**. Unstable conditions, such as ambient wind speed > 3 m/s and low percentage of the time period under the calm condition (wind speed < 0.3 m/s), can disrupt model performance since the Gaussian plume model assumed steady state condition.

The modified Gaussian Plume Model was used to estimate poultry-emitted air pollutant concentration profiles without the presence of a VEB under the same meteorological conditions as the field sampling period. Hourly averaged metrological data, including wind speed, relative humidity, air density, atmospheric pressure, were used for determinations. The output of the model was the average air pollutant concentration ratio ( $\frac{Conc.i}{Conc.ref}$ ), where  $Conc.i$  was the predicted pollutant concentration at selected sampling point,  $Conc.ref$  was the observed pollutant concentration at T1-2 sampling point as a reference point (2-m height sampling point at 2 m distance from the tunnel fan, **Fig. 2**). This reference point was chosen because it was the closest to the tunnel fan, and expected to have the largest air pollutant concentration levels. PM predicted concentration was calculated using **Eq. 1**:

$$Model\ Predicted\ Conc. = (Conc.ref - Conc.bg) * \frac{Conc.i}{Conc.ref} + Conc.bg \quad \text{Equation 1}$$

where  $Conc.ref$  was the PM concentration at T1-2,  $Conc.bg$  was the background PM concentration,  $\frac{Conc.i}{Conc.ref}$  was the model generate ratio for each experiment.

#### Statistical analysis

Ground-level was defined as the 2-m height at Tower 1 (sampling point: T1-2, **Fig. 2**).

Ground-level VEB reduction ratio for  $PM_{2.5}$  and  $NH_3$  were calculated using **Eq.2**:

$$Reduction = \left(1 - \frac{Conc.i - Conc.ref}{Conc.ref}\right) \times 100\% \quad \text{Equation 2}$$

where  $Conc.i$  is the ground-level pollutant concentration at T2 and T3,  $Conc.ref$  is the pollutant concentration at T1-2. Due to the limitation of the sampling conditions, for reduction calculation, T2-3 and T3-4 (**Fig 2a**) sample concentrations were used at Campaign 1 and 2; while T2-2 and T3-2 (**Fig 2b**) were used at Campaign 3.

All statistical analyses, e.g., one-way ANOVA, correlation matrix (Pearson correlation), t-test, standard variance, etc., were performed using Graphpad Prism 7.03 (GraphPad Software, Inc. La Jolla, CA) and Microsoft Excel. Tukey boxplots were used to analyze pollutant concentrations, where each boxplot represented the quartile range of 25<sup>th</sup> percentile (lower) to 75<sup>th</sup> percentile (upper), whiskers: 75<sup>th</sup> percentile plus 1.5 times of inter-quartile range or the maximum data value, and 25<sup>th</sup> percentile minus 1.5 times of inter-quartile range or the minimum data value. The individual points plotted beyond the whiskers of the box-and-whiskers plots were outliers. For  $NH_3$  concentrations below the limit of detection, 0.5 of the value of the limit of detection ( $0.3\mu g/m^3$ ) was used for statistical analyses and figure construction.

## Results and discussion

### Meteorological condition

Microclimatic conditions were recorded at each sampling point during each field sampling campaign. The microclimate can be influenced by the heat emitted from the poultry house through the tunnel fan to the VEB. The average temperature, atmospheric pressure, relative humidity, and wind speed of five day/night experiments from each campaign are presented in **Table 1**. Background wind speed and calm condition percentage are in **SI Table 1** and **SI Fig 1**.

**Table 1.** Microclimatic conditions during daytime and nighttime sampling period of each campaign<sup>a</sup>

	Temperature (°C)		Pressure (kPa)		Relative Humidity (%)		Wind Speed (m/s)	
	Day	Night	Day	Night	Day	Night	Day	Night
Campaign 1	27.7	22.4	91.6	94.9	57.2	67.9	2.3	1.9
	(2.1)	(2.0)	(1.8)	(0.9)	(6.2)	(5.9)	(0.5)	(0.6)
Campaign 2	24.7	20.6	94.2	96.3	65.1	74.3	1.9	1.4
	(2.0)	(1.8)	(1.3)	(0.9)	(6.2)	(4.5)	(0.4)	(0.4)
Campaign 3	25.6	21.3	94.2	96.3	68.7	78.7	1.0	0.9
	(2.7)	(2.3)	(1.3)	(0.9)	(8.2)	(8.2)	(0.4)	(0.4)

<sup>a</sup>Values reported as average values of meteorological conditions of five day (night) field sampling period; standard deviations are below each value in parentheses.

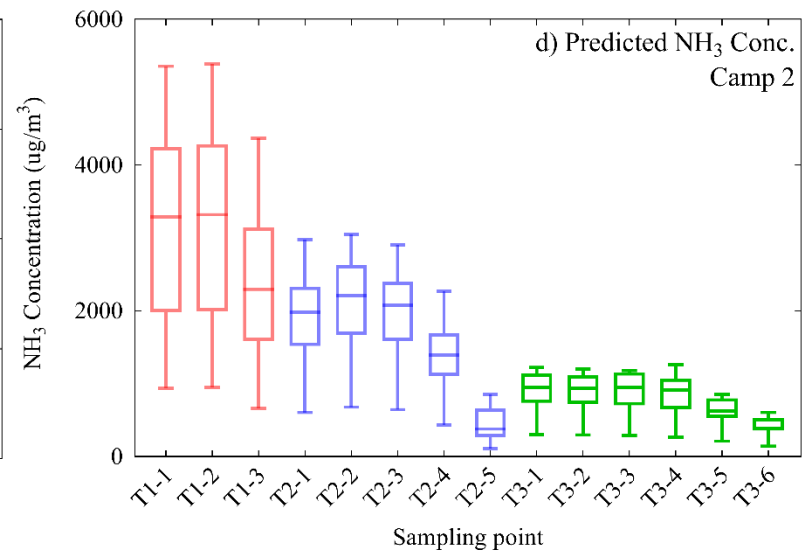
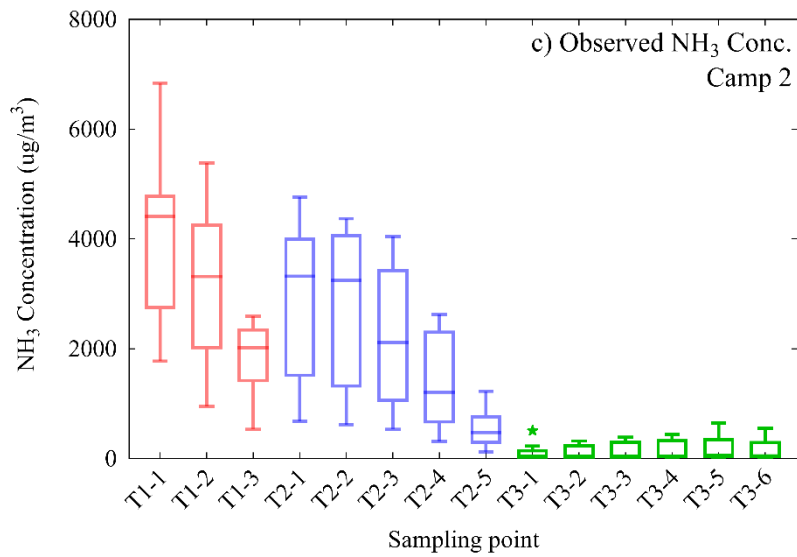
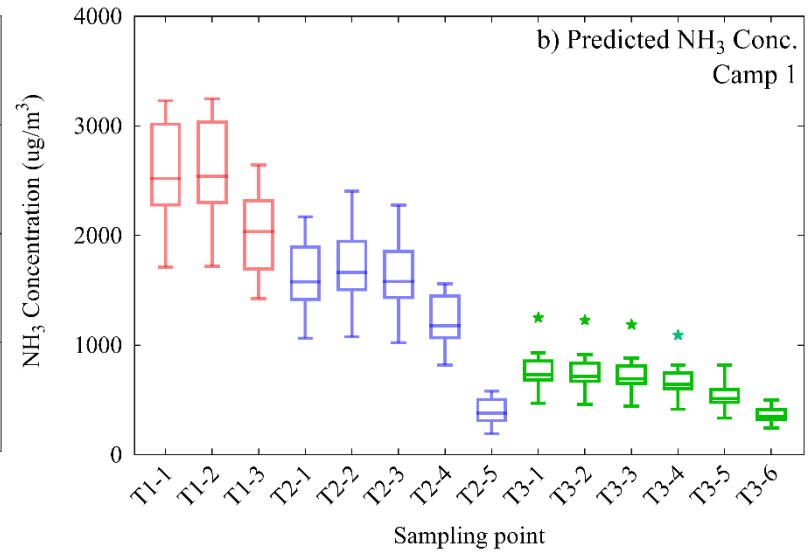
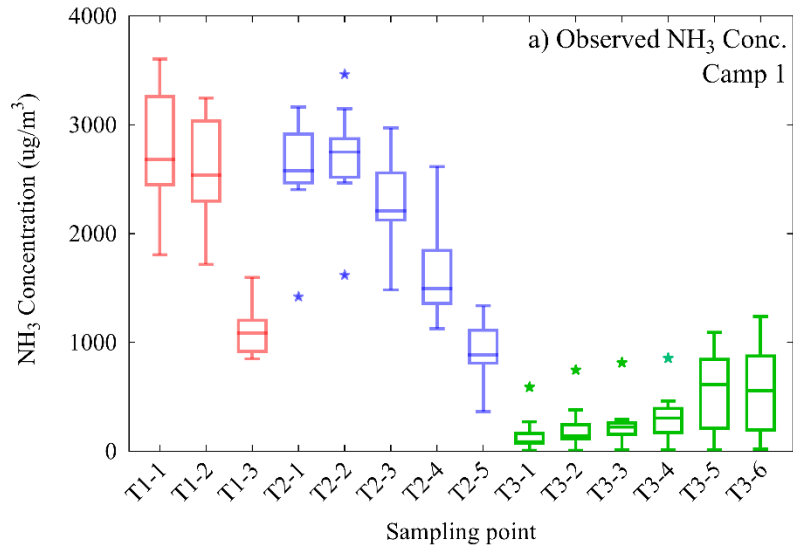
### NH<sub>3</sub> concentrations

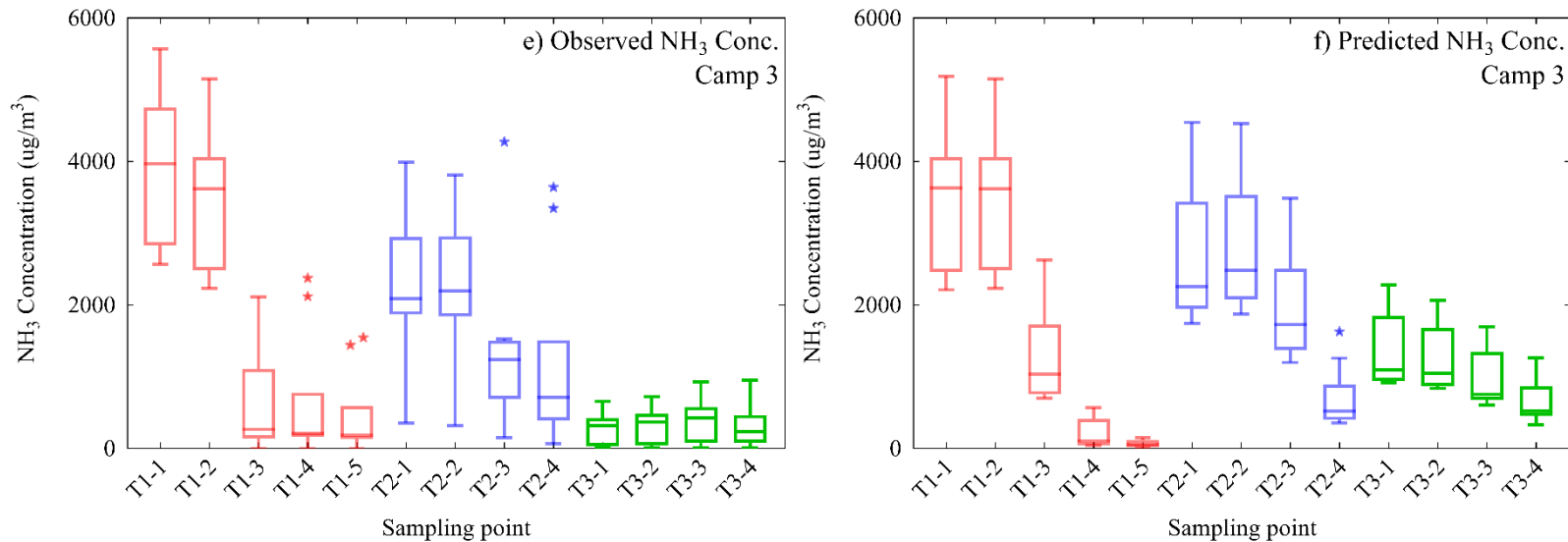
No significant difference ( $p$ -value > 0.05) was observed between diurnal and nocturnal data, therefore, day and night NH<sub>3</sub> concentrations from all experiments in each campaign were

combined for analysis. All NH<sub>3</sub> concentration data from each experiment can be found in **SI Table 2, 3 and 4**. **Fig. 4** showed the Tukey boxplots of the observed NH<sub>3</sub> concentrations from the ten field sampling experiments and the corresponding predicted NH<sub>3</sub> concentrations obtained from the model at the same sampling locations (**Fig. 3**).

NH<sub>3</sub> concentrations decreased with increased heights at T1 and T2 as showed in **Fig. 4a** and **4b** for both observed and predicted data. A similar trend was observed in Campaign 2 (**Fig 4c & 4d**) and Campaign 3 (**Fig 4e & 4f**). The NH<sub>3</sub> concentration decline was more noticeable at the higher sampling points (4.5m, 7.25m, and 10m) of T1 during Campaign 3 for both observed and predicted data. This is consistent with little vertical dispersion of NH<sub>3</sub> in a short distance (**Fig. 3c**). This result was expected because the top of the tunnel fan was at approximately 2 m, and T1 was only 2 m away from the tunnel fan. In addition, the NH<sub>3</sub> concentration was very similar at sampling points from 4.5 to 10 m height on T1 (**Fig. 4e**). The average NH<sub>3</sub> concentration at T1-3 was much lower than the average NH<sub>3</sub> concentration at T2-3 in Campaign 3 (**Fig 4e** and **4f**). T2 was set up between the grass row and the tree row of the VEB, so most likely the NH<sub>3</sub> was trapped by the VEB.

T3 had significantly lower observed concentration levels ( $p$ -value < 0.001) for all three campaigns at ground level (< 3 m). The observed NH<sub>3</sub> concentrations showed a slight increase as the height increased (**Fig 4a, 4c** and **4e**), while the predicted data showed the opposite trend (**Fig 4b, 4d**, and **4f**). The predicted data was only under the influence of dispersion, while both dispersion and VEB played a role in affecting the observed data. This result showed the high potential of VEB in further trapping NH<sub>3</sub> emitted from the poultry houses.





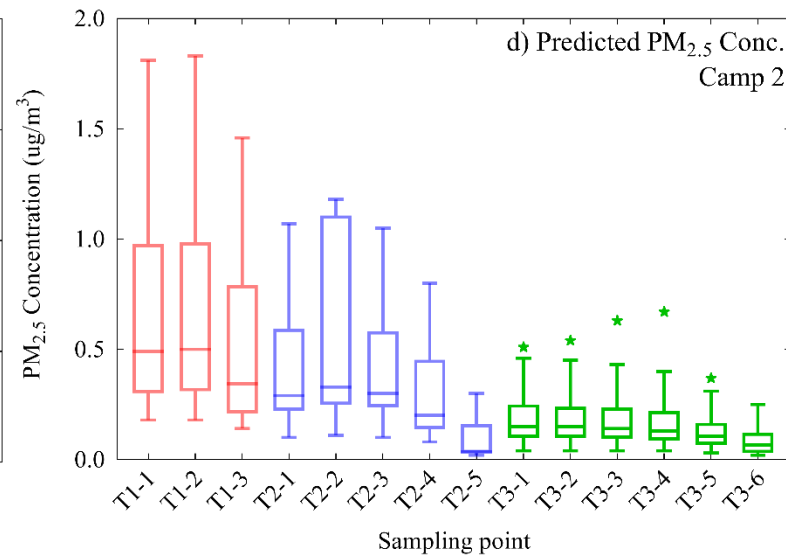
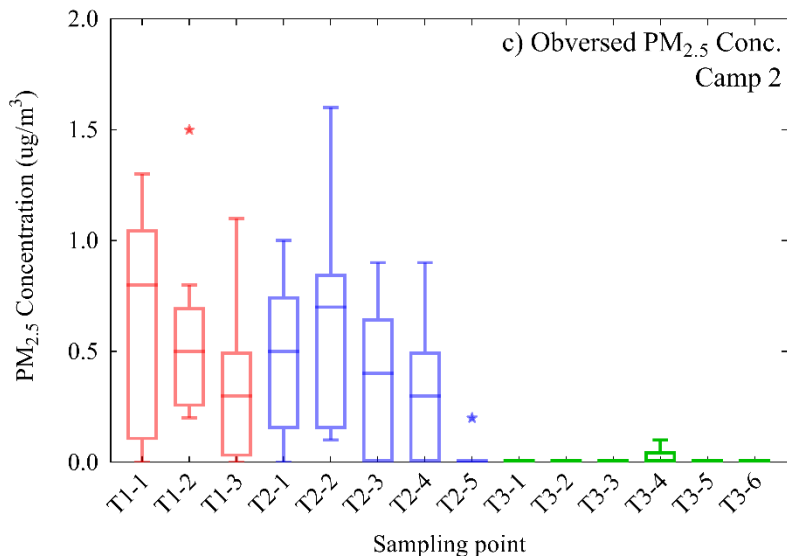
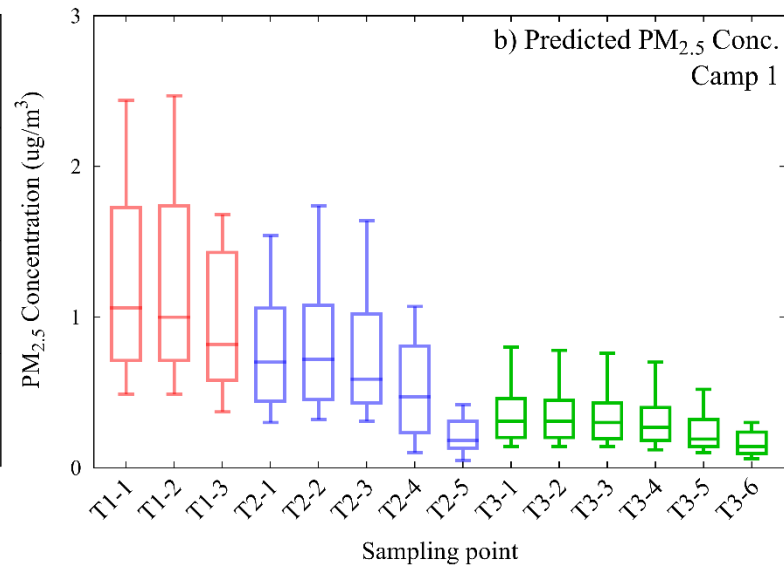
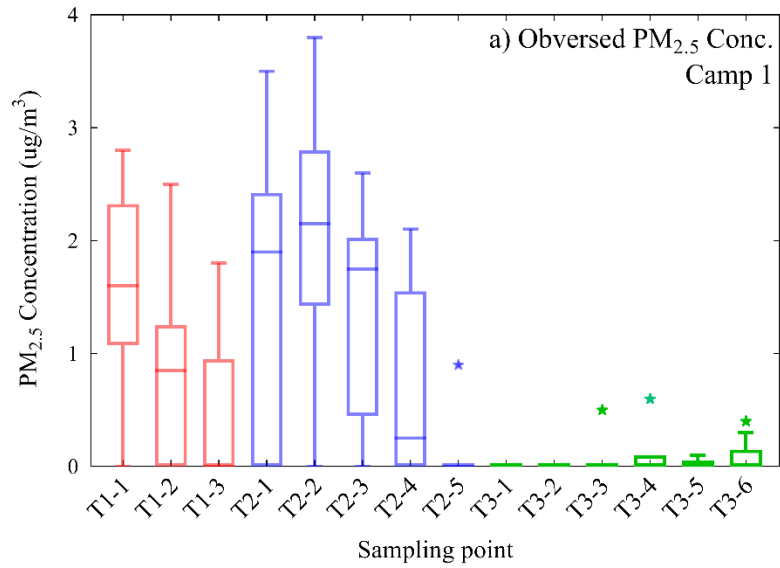
**Figure 4.** Tukey box-plots of ammonia concentrations at different sampling points. The boxplot represents the quartile range of the 25<sup>th</sup> percentile (lower) to the 75<sup>th</sup> percentile (upper). The whiskers are the 75<sup>th</sup> percentile plus 1.5 times of inter-quartile range or the maximum data value and the 25<sup>th</sup> percentile minus 1.5 times of inter-quartile range or the minimum data value. The individual points that are plotted beyond the whiskers of the box-and-whiskers plots were outliers. Observed NH<sub>3</sub> concentrations were from ten sampling experiments of each campaign, and the predicted NH<sub>3</sub> concentrations were from model calculation with the same meteorological conditions during the same sampling period. a) Observed NH<sub>3</sub> concentrations at Campaign 1; b) Predicted NH<sub>3</sub> concentrations at Campaign 1; c) Observed NH<sub>3</sub> concentrations at Campaign 2; d) Predicted NH<sub>3</sub> concentrations at Campaign 2; e) Observed NH<sub>3</sub> concentrations at Campaign 3; and f) Predicted NH<sub>3</sub> concentrations at Campaign 3. Sampling points were shown in the **Fig. 2**. Tower 1 (red) was 2 m away from the tunnel fan; Tower 2 (purple) was 6 m away from the tunnel fan; Tower 3 (green) was 20 m away from the tunnel fan.

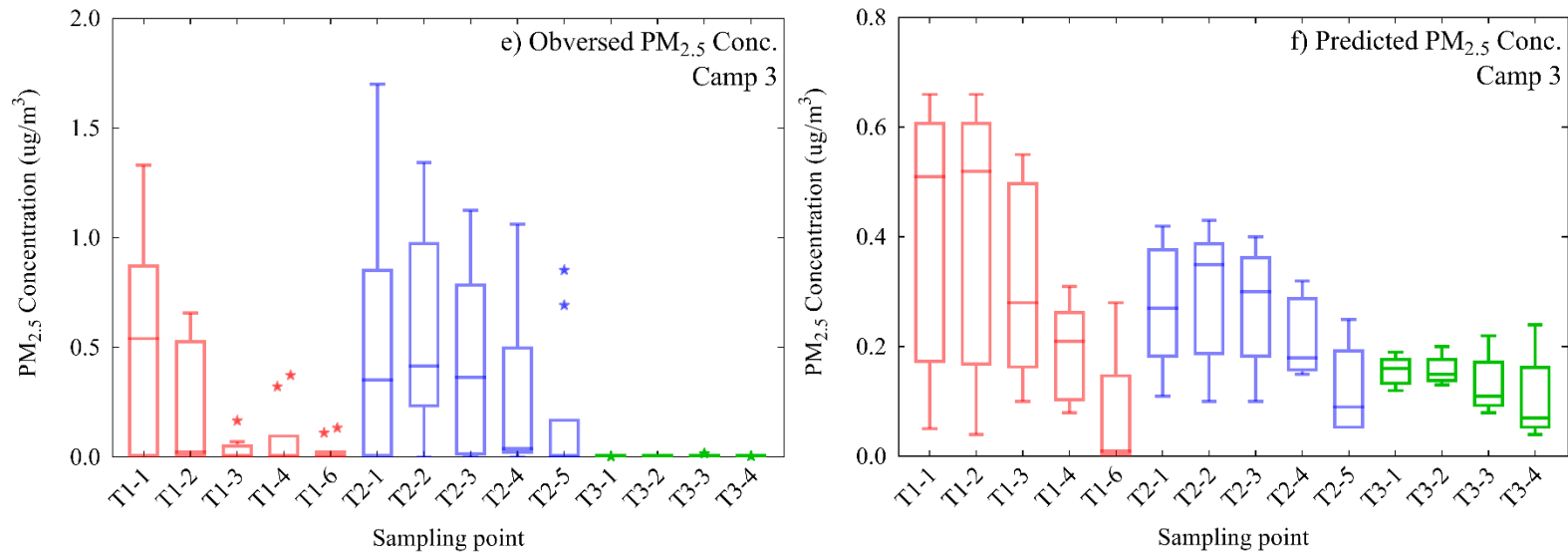


### PM<sub>2.5</sub> concentrations

As with the NH<sub>3</sub> concentrations, no significant differences were observed PM<sub>2.5</sub> concentration data between diurnal and nocturnal experiments within the same campaign ( $p$ -value > 0.05). All PM<sub>2.5</sub> concentration data from each experiment can be found in **SI Table 2, 3** and **4**. **Fig. 5** showed the Tukey boxplots of the observed PM<sub>2.5</sub> concentrations from the ten field experiments at each sampling point and the corresponding predicted PM<sub>2.5</sub> concentrations obtained from model calculations. Similar to the trends observed with NH<sub>3</sub> concentrations, PM<sub>2.5</sub> concentrations decreased with increased height at T1 and T2 (**Fig. 5**) for both observed and predicted data due to the same reason, although the trends were not as dramatic. It was possible that gaseous NH<sub>3</sub> had already contributed to PM<sub>2.5</sub> concentration; and it was more difficult for VEB to trap or adsorb PM<sub>2.5</sub> than NH<sub>3</sub>.

T3 had significantly lower observed PM<sub>2.5</sub> concentration levels ( $p$ -value < 0.05) than on T1 and T2 for all three campaigns at ground level (< 3 m). The observed PM<sub>2.5</sub> concentrations were close to 0 for most sampling points on T3, which were much lower than the predicted PM<sub>2.5</sub> concentration levels at all heights (**Fig 5**). This suggests that the VEB was very effective in trapping PM<sub>2.5</sub> emissions from the poultry house.





**Figure 5.** . Tukey box-plots of PM<sub>2.5</sub> concentrations at different sampling points. The boxplot represents the quartile range of the 25<sup>th</sup> percentile (lower) to the 75<sup>th</sup> percentile (upper). The whiskers are the 75<sup>th</sup> percentile plus 1.5 times of inter-quartile range or the maximum data value and the 25<sup>th</sup> percentile minus 1.5 times of inter-quartile range or the minimum data value. The individual points that are plotted beyond the whiskers of the box-and-whiskers plots were outliers. Observed PM<sub>2.5</sub> concentrations were from ten sampling experiments of each campaign, and the predicted PM<sub>2.5</sub> concentrations were from model calculation with the same meteorological conditions during the same sampling period. a) Observed PM<sub>2.5</sub> concentrations at Campaign 1; b) Predicted PM<sub>2.5</sub> concentrations at Campaign 1; c) Observed PM<sub>2.5</sub> concentrations at Campaign 2; d) Predicted PM<sub>2.5</sub> concentrations at Campaign 2; e) Observed PM<sub>2.5</sub> concentrations Campaign 3; and f) Predicted PM<sub>2.5</sub> concentrations at Campaign 3. Sampling points were shown in the **Fig. 2**. Tower 1 (red) was 2 m away from the tunnel fan; Tower 2 (purple) was 6 m away from the tunnel fan; Tower 3 (green) was 20 m away from the tunnel fan.

### Correlation between PM<sub>2.5</sub>, NH<sub>3</sub>, and meteorological factors

Pearson correlation calculations were carried out for PM<sub>2.5</sub> concentrations with NH<sub>3</sub> concentrations and the meteorological conditions at the same sampling point (**Table 2**). As expected, PM<sub>2.5</sub> and NH<sub>3</sub> were strongly correlated since NH<sub>3</sub> is an important precursor to PM<sub>2.5</sub>. PM<sub>2.5</sub> concentrations were positively correlated with wind speed, suggesting that with higher wind speeds, PM<sub>2.5</sub> was transported further and therefore higher PM<sub>2.5</sub> concentrations were observed. Temperature had a slight positive correlation with PM<sub>2.5</sub> concentrations during Campaign 2 and 3, but in Campaign 1 temperature was not correlated with PM<sub>2.5</sub>. For all the campaigns, longer distance and higher heights would result in lower PM<sub>2.5</sub> concentration due to dilution effect.

**Table 2** Pearson correlation matrix for PM<sub>2.5</sub> concentration with NH<sub>3</sub> concentration, meteorological factors of temperature (T), atmospheric pressure (P), relative humidity (RH), wind speed (WS), and sampling heights and distance to the tunnel fan.

	NH <sub>3</sub>	T	P	RH	WS	Height	Distance
Camp 1	0.72	-0.05	-0.03	-0.40	0.44	-0.17	-0.51
Camp 2	0.55	0.34	-0.11	-0.14	0.44	-0.09	-0.41
Camp 3	0.55	0.30	-0.14	0.18	0.36	-0.31	-0.30

Pearson correlation calculations were carried out for NH<sub>3</sub> concentrations with the meteorological conditions at the same sampling point (**Table 3**), which were very similar to the correlations of PM<sub>2.5</sub>.

**Table 3.** Pearson correlation matrix for NH<sub>3</sub> with meteorological factors of temperature (T), atmospheric pressure (P), relative humidity (RH), wind speed (WS), and sampling heights and distance to the tunnel fan.

	T	P	RH	WS	Height	Distance
Camp 1	-0.06	0.12	-0.11	0.68	-0.07	-0.79
Camp 2	0.34	0.02	0.18	0.29	-0.16	-0.72
Camp 3	0.17	0.08	0.44	0.00	-0.40	-0.46

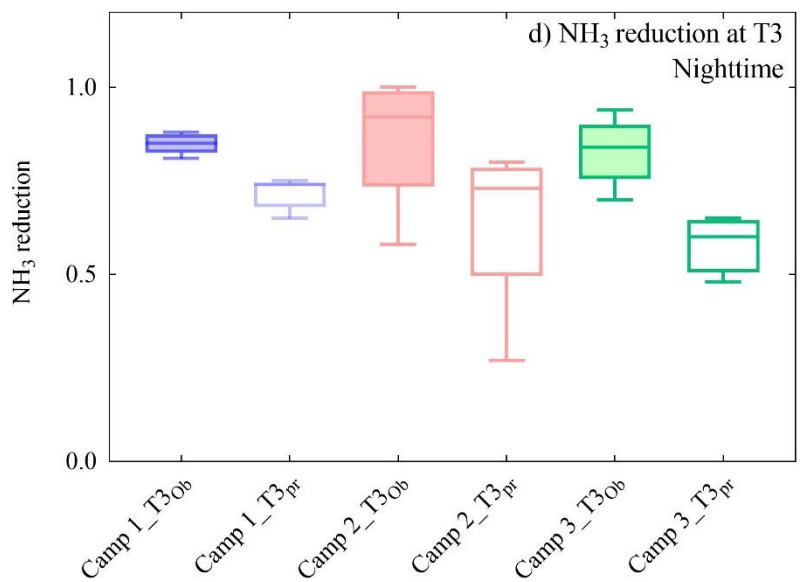
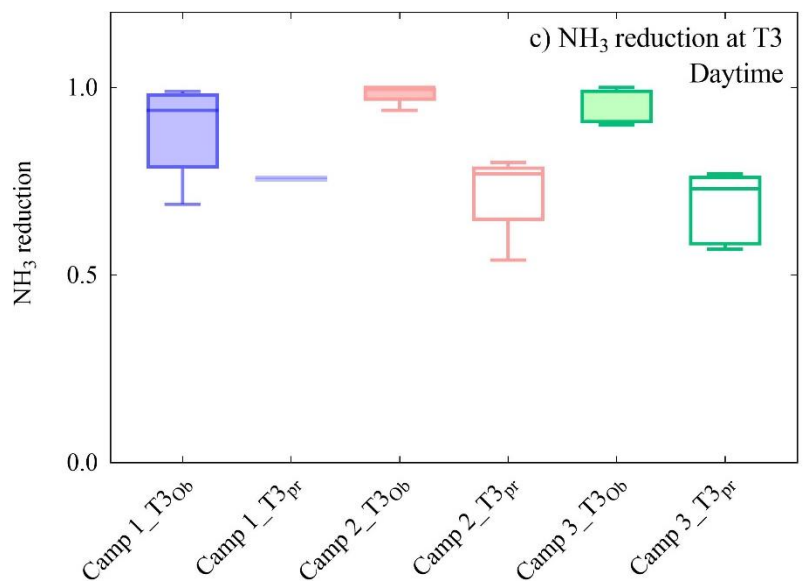
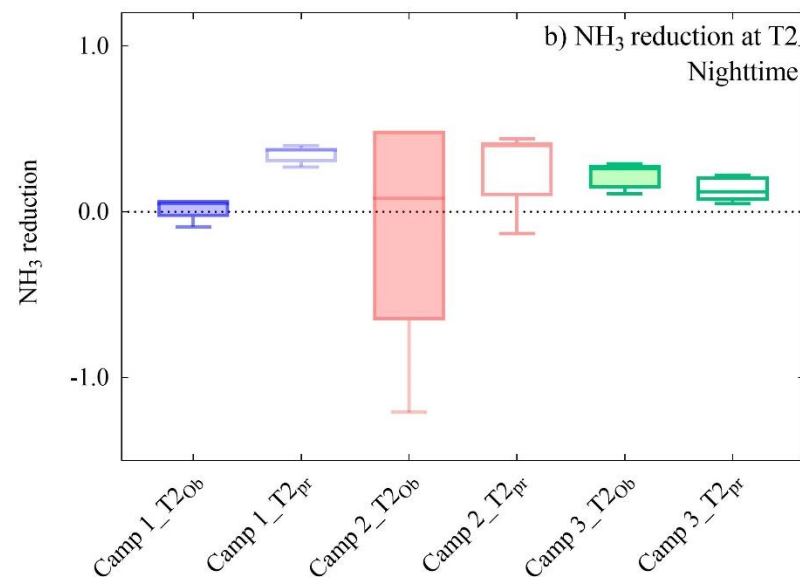
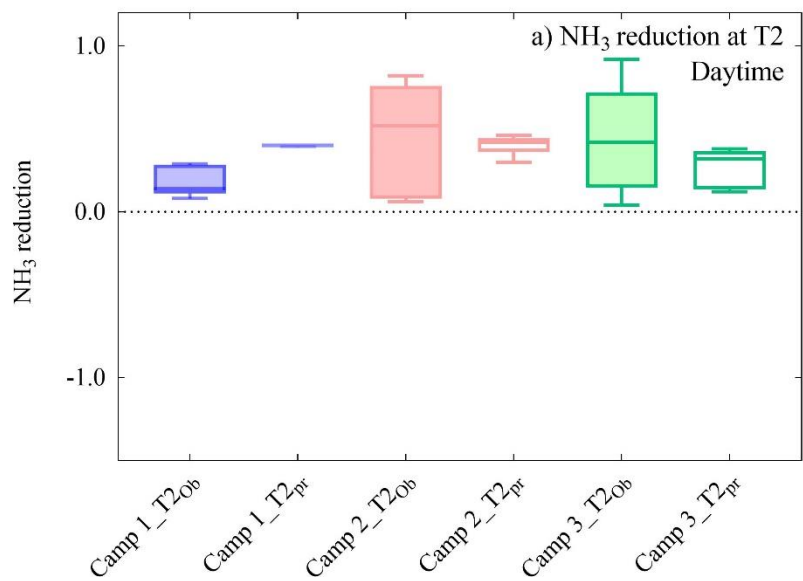
#### Ground-level NH<sub>3</sub> concentration reduction

The reduction of NH<sub>3</sub> concentrations at ground level (2 m) were calculated for each experiment in each campaign. These calculations were carried out by comparing the ground-level NH<sub>3</sub> concentrations on T1 with T2 (**Figs. 6a** and **6b**) and with T3 (**Figs. 6c** and **6d**). This was done for both observed and predicted data. Significant differences were observed between diurnal and nocturnal reduction data for both observed and predicted data ( $p$ -value < 0.05). These results are summarized in Tukey box-plots (**Fig. 6**).

The observed NH<sub>3</sub> reduction ratio at T2 during the day (**Fig. 6a**) for Campaign 1 was lower than the predicted ratio. The observed and predicted reduction was similar in Campaign 2 and 3. Similar results were observed for the nocturnal data (**Fig. 6b**), although the values were lower during the night. This may be due to the calmer and more stable meteorological conditions (**Table 1**) during the nighttime, discouraging the pollutant dispersion motions.

The observed and predicted NH<sub>3</sub> reduction ratios at T3 were noticeably higher than at T2. In addition, the observed NH<sub>3</sub> reduction ratios at T3 were much larger than predicted ratios during both day and night for all campaigns. Based on five sampling experiments, averaged observed NH<sub>3</sub> reduction efficiencies were 90% ± 12%, 98% ± 3%, and 90% ± 9% during the daytime and 85% ± 3%, 87% ± 17%, 83% ± 9% during the nighttime for Campaigns 1, 2, and 3, respectively. Based on five model estimation using the same metrological conditions as the

sampling experiments, averaged predicted NH<sub>3</sub> reduction efficiencies were 76% ± 1%, 73% ± 11%, and 68% ± 9% during the daytime and 72% ± 4%, 66% ± 22%, 58% ± 7% during the nighttime for Campaign 1, 2, and 3, respectively. These latter values indicate the amount of reduction due to dispersion. Thus, VEB reduced NH<sub>3</sub> concentrations further by 15% to 25% during the daytime and 13% to 25% during the nighttime.



**Figure 6.** Tukey box-plots of NH<sub>3</sub> concentration reduction ratios. The boxplot represents the quartile range of the 25<sup>th</sup> percentile (lower) to the 75<sup>th</sup> percentile (upper). The whiskers are the 75<sup>th</sup> percentile plus 1.5 times of inter-quartile range or the maximum data value and the 25<sup>th</sup> percentile minus 1.5 times of inter-quartile range or the minimum data value. Observed NH<sub>3</sub> concentration reduction ratios were from five sampling experiments (day/night) of each campaign, and the predicted NH<sub>3</sub> concentrations were from model calculation with the same meteorological conditions during the same sampling period. a) NH<sub>3</sub> concentration reduction ratios at T2 during the daytime; b) NH<sub>3</sub> concentration reduction ratios at T2 during the nighttime; c) NH<sub>3</sub> concentration reduction ratios at T3 during the daytime; d) NH<sub>3</sub> concentration reduction ratios at T3 during the nighttime. Solid-box plots represent observed data, whereas open-box plots represent model-predicted data.

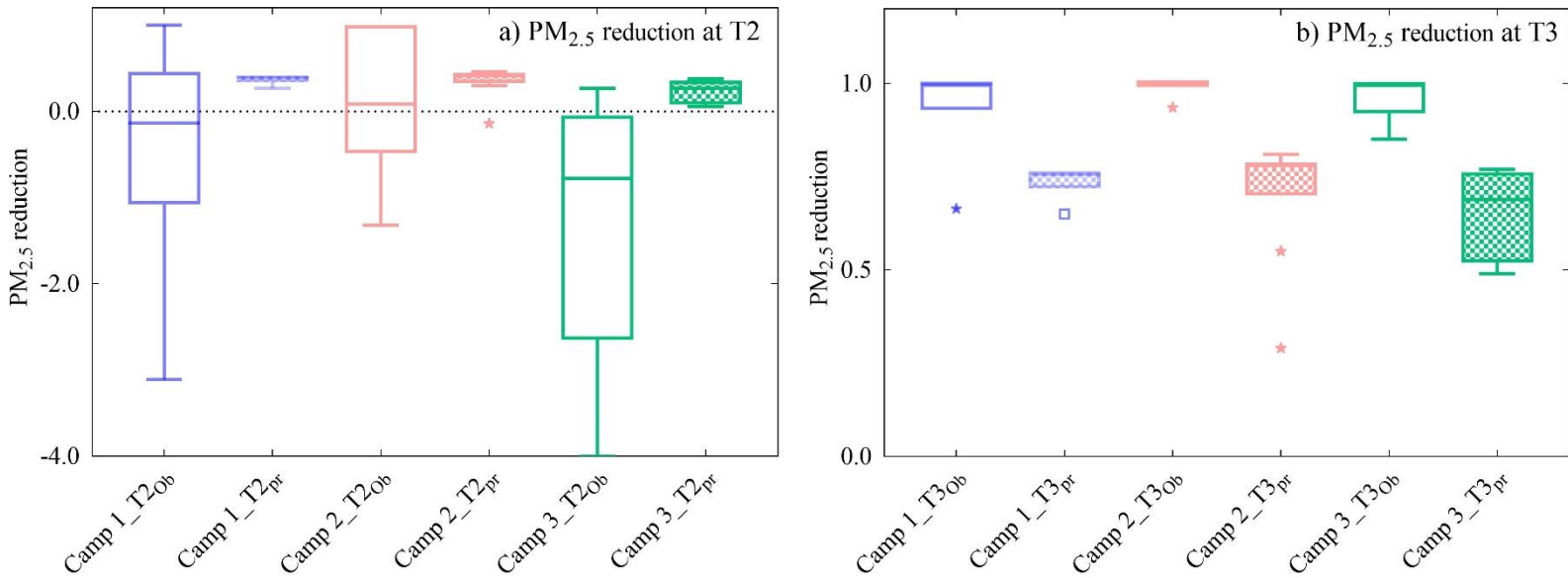


#### Ground-level: PM<sub>2.5</sub> concentration reduction

The reduction of PM<sub>2.5</sub> concentrations at ground level (2 m) were calculated for each experiment in each campaign. These calculations were carried out by comparing the ground-level NH<sub>3</sub> concentrations on T1 with T2 (**Fig. 7a**) and with T3 (**Fig. 7b**). This was done for both observed and predicted data. No significant differences were observed between diurnal and nocturnal reduction data for both observed and predicted data ( $p$ -value > 0.05). These results are summarized in Tukey box-plots (**Fig. 7**).

The observed PM<sub>2.5</sub> concentration reduction ratios at T2 were lower than predicted ratios for all the campaigns (**Fig. 7a**). In addition, more than half the observed PM<sub>2.5</sub> concentration reduction ratios were negative, which indicated that PM<sub>2.5</sub> had accumulated inside the buffer.

The observed and predicted PM<sub>2.5</sub> concentration reduction ratios at T3 were higher than at T2 (**Fig. 7b**). In addition, the observed PM<sub>2.5</sub> concentration reduction ratios behind the VEB at T3 were almost 100% for all three campaigns and were higher than the predicted ratios. Based on ten sets of sampling experimental and model estimated data, averaged observed PM<sub>2.5</sub> reduction efficiencies were 94% ± 12%, 99% ± 2%, and 97% ± 7% and averaged predicted PM<sub>2.5</sub> reduction efficiencies were 74% ± 4%, 71% ± 16%, and 66% ± 12% for Campaign 1, 2, and 3, respectively. Again, these latter values indicate the amount of reduction due to dispersion. Thus, VEB reduced PM<sub>2.5</sub> concentrations further by 20% to 30%.



**Figure 7.** Tukey box-plots of PM<sub>2.5</sub> concentration reduction ratios. The boxplot represents the quartile range of the 25<sup>th</sup> percentile (lower) to the 75<sup>th</sup> percentile (upper). The whiskers are the 75<sup>th</sup> percentile plus 1.5 times of inter-quartile range or the maximum data value and the 25<sup>th</sup> percentile minus 1.5 times of inter-quartile range or the minimum data value. The individual points that are plotted beyond the whiskers of the box-and-whiskers plots were outliers. Observed PM<sub>2.5</sub> concentration reduction ratios were from ten sampling experiments of each campaign, and the predicted PM<sub>2.5</sub> concentration reduction ratios were from model calculation with the same meteorological conditions during the same sampling period a) PM<sub>2.5</sub> concentration reduction ratios at T2; b) PM<sub>2.5</sub> concentration reduction ratios at T3. Solid-box plots represent observed data, whereas open-box plots represent model-predicted data.

Correlation between ground-level PM<sub>2.5</sub> concentration reduction ratio and NH<sub>3</sub> concentration reduction ratio and meteorological factors

A strong positive correlation exists between the PM<sub>2.5</sub> concentration reduction ratio and the NH<sub>3</sub> concentration reduction ratio at the same sampling point during both day and nighttime (**Table 4**). This indicates that reducing NH<sub>3</sub> concentrations will mostly likely decrease PM<sub>2.5</sub> concentrations. A positive correlation was also observed between PM<sub>2.5</sub> concentration reduction ratio and distance. This was expected because longer distances allow further dispersion. No correlations were observed between PM<sub>2.5</sub> concentration reduction ratio and the meteorological conditions. Similar trends were observed between the NH<sub>3</sub> concentration reduction ratio and distance and the meteorological factors (**Table 5**).

**Table 4.** Pearson correlation matrix for ground-level PM<sub>2.5</sub> concentration reduction ratio with NH<sub>3</sub> concentration reduction ratio, meteorological factors of temperature (T), atmospheric pressure (P), relative humidity (RH), wind speed (WS), and sampling distance to the tunnel fan.

	NH <sub>3</sub> Reduction	T	P	RH	WS	Distance
Daytime	0.66	-0.14	0.16	0.29	0.21	0.61
Nighttime	0.59	-0.13	0.09	-0.21	0.09	0.64

**Table 5.** Pearson correlation matrix for NH<sub>3</sub> reduction rate with meteorological factors of temperature (T), atmospheric pressure (P), relative humidity (RH), wind speed (WS), and sampling distance to the tunnel fan.

	T	P	RH	WS	Distance
Daytime	0.13	-0.11	-0.08	0.09	0.88
Nighttime	0.02	-0.02	-0.17	0.13	0.85

Conclusions

This study illustrated that VEBs are an effective practice in mitigating PM<sub>2.5</sub> and NH<sub>3</sub> emitted from the poultry houses. It has also demonstrated the close correlation between PM<sub>2.5</sub> and NH<sub>3</sub> concentrations and reductions. The model served as a control to provide PM<sub>2.5</sub> and NH<sub>3</sub> concentration profiles under no VEB present conditions with the same meteorological factors as the sampling period. The model helped to separate the dispersion and dilution factors from the measured data. By comparing field-observed and model-predicted data, the VEB was responsible for an increase in the reduction of PM<sub>2.5</sub> concentrations from 20% to 30%, and of NH<sub>3</sub> concentrations from 13% to 25%.

## Chapter 5: Poultry house emissions: source for volatile organic compounds with ozone formation potential

### Abstract

Ground-level ozone is formed when volatile organic compounds (VOCs) react with hydroxyl radicals and nitrogen oxides in the presence of ultraviolet light.

Research has typically focused on the release and control of VOCs from hydrocarbon processing, however, agricultural activities, such as poultry production, can also be VOC sources and potentially contribute to ozone pollution. Therefore, this study examines the emission C<sub>2</sub> - C<sub>6</sub> VOCs emitted from poultry houses and the use of a vegetative environmental buffer (VEB) as a potential mitigation strategy. Sampling campaigns were conducted at two farms, one with and one without a VEB. Of the compounds measured, methanol, ethanol, and acetone were found to come primarily from the poultry houses and had the largest ozone formation potential (OFP). Additional local sources were evident for other VOCs observed near the poultry houses. A substantial decrease in the OFP for methanol was observed as a function of distance from the poultry house at the farm with the VEB. These results suggest that besides a visual barrier and particulate screen, VEBs can provide some control on the VOCs emitted from poultry production.

### Introduction

Ozone is one of the six criteria air pollutants identified in the Clean Air Act by the United States Environmental Protection Agency (US EPA) and is the primary ingredient in photochemical smog. Ground-level ozone is a concern because it can cause severe respiratory problems among older adults and young children and can

negatively affect the trees and agricultural crops (US EPA, 2016). Ozone concentrations can reach unhealthful levels when the temperature is high and few or no clouds are present with little or no wind. The average ozone level is the highest usually during April to October. In 2015, the US EPA strengthened the National Ambient Air Quality Standards (NAAQS) for ground-level ozone. The current NAAQS for ground-level ozone is an eight-hour average concentration of 70 ppb (US EPA, 2016).

Ground-level ozone is formed in the atmosphere when volatile organic compounds (VOCs) react with hydroxyl radicals and nitrogen oxides in the presence of ultraviolet light. However, some VOCs react quickly with hydroxyl radicals (e.g., xylenes) and are referred to as reactive organic gases, other VOCs (e.g., methane) are virtually non-reactive with hydroxyl radicals, while short chain alcohols are moderately reactive (Carter, 1994)(Atkinson, 1989). Therefore, decreasing the amount of VOCs released to the atmosphere is critical to reducing potential ozone pollution.

Ground-level ozone level in the Chesapeake Bay region has also become a concern. Over 30 counties in this area did not meet the new EPA ground-level ozone requirement during 2012 to 2014 (EPA, 2015a), and those areas are likely to be designated as nonattainment areas in late 2017 (EPA, 2015a). In addition, high levels of NO<sub>x</sub> primarily due to massive electric power plants and interstate traffic are released to the atmosphere in this region (US EPA, 2016a). With the increasing encroachment of urbanization into agricultural lands, the ozone formation potential of the VOCs released from agriculture need to be considered.

The Chesapeake Bay region and Delmarva Peninsula have become one of the major poultry-producing areas because of the large markets from New York to Washington DC. In 2016, Virginia, Maryland, Delaware, and Pennsylvania together produced almost 9% of the broilers in the US (USDA National Agricultural Statistics Service, 2017). These four states make up a developed broiler belt (areas where chickens outnumber people) in the Chesapeake Bay region (Pew Environment Group, 2011). This rapid expansion and consolidation of industrialized poultry operations has raised concerns about the air pollutants emitted from these facilities and the negative impacts of these pollutants on the public health and the surrounding environment (Palmquist, Roka, & Vukina, 1997). Further, odor emitted by concentrated animal feeding operations (CAFOs) can be a significant social problem and can negatively affect rural and state economies (Tyndall & Colletti, 2007). CAFOs can also emit numerous VOCs to the atmosphere (Schiffman et al., 2001). Inside the CAFO facilities, the most abundant VOCs observed were acetic acid, 2,3-butanedione, methanol, acetone, and ethanol (Trabue et al., 2010). Others have identified that the highest VOC levels were around ventilation areas (Blunden, Aneja, & Lonneman, 2005). For poultry operations the primary VOC sources are manure, waste bedding, fertilizer and crop residues, and feathers. Although studies have been conducted measuring and identifying VOCs inside poultry houses, little VOC emission data are available for outside the poultry houses.

Vegetative environmental buffers (VEB) have been introduced to poultry producers as a cost-efficient practice for air pollutant remediation. VEBs are rows of grasses, shrubs and trees purposefully planted surrounding the CAFOs, which also

provide a more appealing visual for the facilities. Previous studies have reported that VEBs can reduce VOCs in swine farms (Parker et al., 2012; Tyndall & Colletti, 2007). Yet no specific research has been done relate to poultry houses.

The objective of this study is to develop VOC specific concentration profiles which begin near the sidewall ventilation fans and extend perpendicularly outward from poultry houses, access the emission sources for the various VOCs, evaluate the potential ozone formation from poultry-emitted VOCs, and examine the ability of VEBs to mitigate this potential risk. Time-integrated air samples were collected at multiple locations and heights outside of two poultry farms in two air sampling campaigns between very late spring to summer. This time period has higher temperatures, which leads to increased poultry house ventilation, and presumably to higher VOC emissions. Air samples were analyzed for quantifying nine non-methane VOCs (C2 - C6 molecular weight range): propene, methanol, ethanol, acetone, acetonitrile, propanol, hexane, butanol, and butanal. These VOCs were previously reported with relatively high concentrations inside the poultry houses and CAFOs (Blunden et al., 2005; Ni et al., 2012; Trabue et al., 2010), especially during warmer and active feeding period. In addition, these compounds have larger hydroxy radical reaction rates (Atkinson, 1989).

### Materials and Methods

#### Site description

Two commercial poultry farms were chosen for the field air sampling campaigns (**Fig. 1**). Farm 1 was located in southeastern Pennsylvania and consisted of two poultry houses (152 m length \* 15 m width) with approximately 25,000 boilers



per house. This facility is a certified organic commercial poultry farm that uses organic-approved feed and litter amendments. The farm produces free-range chickens by providing them with fenced-in outdoor access. Each flock was raised for 50 days with a 10-day down time in between flocks when the litter was removed and new bedding was placed. The house included five 1.2-m tunnel fans on both sides of the houses at the tunnel end; four 0.9-m sidewall fans (35-m apart) were located on the south sidewall. None of the sidewall fans were used during the field campaign. A vegetative environmental buffer (VEB) was located parallel to the first house. This VEB consisted of a row of switch-grass and giant miscanthuses, which were planted in 2012, and a row of hybrid Austere willow trees, which was planted in 2007. The height of the willow tree and grasses were approximately 10 m and 3 m respectively. The distance between the grass portion of the VEB and the tunnel fans was approximately 5 m.

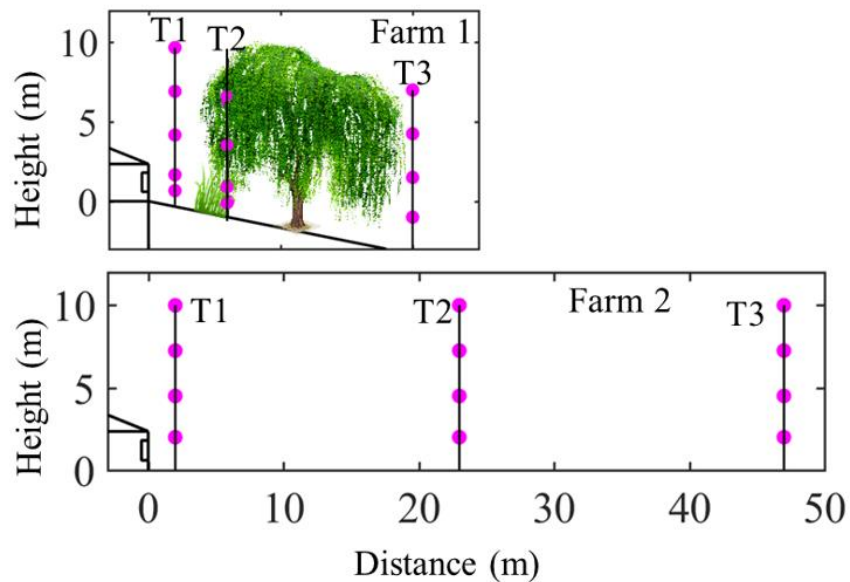
Farm 2 was located at Delaware and consisted of two poultry houses (122 m length \* 21 m width) with approximately 28,000 boilers per house. This facility is a typical CAFO poultry farm, where each flock was raised on used litter for 60 days with a 10-day inactive time between flocks. Mechanical ventilation of the poultry house was accomplished by five 1.2-m tunnel fans on both sides of the house.

#### Air sampling

Two air sampling campaigns were carried out, one at Farm 1 in August 2015 and one at Farm 2 in late May 2015. At Farm 1, three 10-m sampling towers with multiple sampling heights were deployed perpendicularly to the primary ventilation fans of house one at distances of 2, 6, and 20 m. The sampling heights above ground

level for Tower 1 (T1) were 1, 2, 4.5, 7.25, and 10 m; Tower 2 (T2) were 1, 2, 4.5, and 7.25 m; and Tower 3 (T3) were 2, 4.5, 7.25, and 10 m (**Fig. 1**). There was a ground-level elevation drop of about 1 m between T1 and T2 and a drop of about 3 m between T1 and T3. A background sampler (S3) was deployed at approximately 150 m away northwest from the tunnel fans.

At Farm 2, three 10-m sampling towers with multiple sampling heights were deployed perpendicularly to the primary ventilation fans of house one at distances of 2, 23, and 47 m. The sampling heights above ground level for all towers (T1, T2 and T3) were 2, 4.5, 7.25, and 10 m (**Fig. 1**). A background sampler (S5) was deployed at approximately 70 m away east from the tunnel fans.



**Figure 1.** Experimental set up for two farms with sampling points (purple dots). Farm 1, with a 3-m height slope, had Tower 1, 2, and 3 set up at distances of 2, 6, and 20 m to the primary fan. The sampling heights on the towers were: T1 (1, 2, 4.5, 7.25, and 10 m); T2 (1, 2, 4.5, and 7.25 m); and T3 (2, 4.5, 7.25, and 10 m). Farm 2 had Tower 1, 2, and 3 set up at distance of 2, 23, 47m to the primary fan. The sampling heights on the towers were the same: 2 m, 4.5 m, 7.25 m and 10 m.

US EPA Method TO-15 was used to collect VOCs (Blunden et al., 2005; Trabue et al., 2010) with using 1-L amber glass canisters (Bottle-Vac) coupled with a filtered restrictor to afford 2-hr integrated air samples (Entech Instruments, Inc., Simi Valley, California). The filter of the restrictor ensured that particulates were not collected. All canisters were cleaned and evacuated for 20 cycles and reached a final evacuation of -1.04 atm using an Entech 3100A canister cleaner automatic system (Entech Instruments, Inc., Simi Valley, California). Five daytime and five nighttime sampling experiments were performed at during each campaign. One duplicate sample was collected in each experiment. Samples were transported to the laboratory and were analyzed within two weeks after collection. Meteorological conditions (temperature, pressure, relative humidity, wind speed, and wind direction) were recorded by HOBO U30 Station 3.0.0 (Onset Computer Corporation, Bourne, Massachusetts) (**SI Table 1, Table 2**).

#### Sample analyses

A 3400A auto sampler and 7200A pre-concentrator (Entech Instruments, Inc., Simi Valley, California) were used to prepare the gas samples prior to injection into an Agilent 6980N gas chromatograph equipped with a 5973 mass spectrometer (Agilent Technologies, Inc.). The pre-concentrator used three gas concentrating stages to trap water and CO<sub>2</sub> prior to the injection onto a GC column (Rxi-1ms, 60m \* 0.32mm \* 0.1µm Restek Corporation, Bellefonte, Pennsylvania). Instrument settings were as follows: 35 °C hold 5min, ramp 5 °C/min to 140 °C, ramp 25 °C/min to 220 °C, and hold 5 min; inlet temperature 175°C and flow (He) = 1.5 mL/min, splitless. The mass spectrometer was operated under both scan and sim modes with

electron ionization mode. Calibration gas standards (10 ppm) with a mixture of 8 standard gases were custom made (Restek Corporation, Bellefonte, Pennsylvania). The detection limit of each VOC was as follow: butanal ( $6 \mu\text{g}/\text{m}^3$ ), butanol ( $6 \mu\text{g}/\text{m}^3$ ), hexane ( $7 \mu\text{g}/\text{m}^3$ ), propanol ( $5 \mu\text{g}/\text{m}^3$ ), acetone ( $5 \mu\text{g}/\text{m}^3$ ), acetonitrile ( $3 \mu\text{g}/\text{m}^3$ ), ethanol ( $4 \mu\text{g}/\text{m}^3$ ), methanol ( $3 \mu\text{g}/\text{m}^3$ ), and propene ( $3 \mu\text{g}/\text{m}^3$ ). Dilution of calibration gases was performed by a dynamic dilution system 4600A (Entech Instruments, Inc., Simi Valley, California).

#### Statistical analyses

All statistical analyses, e.g one-way ANOVA, paired t-test, standard variance, etc., were performed using SPSS (v.23, SPSS Inc., Chicago, Illinois) and Microsoft Excel. Relative VOC concentrations were used in the data analysis, because the range of concentrations was very large between experiments. Relative concentrations ( $\frac{\text{Conc.}}{\text{T1 ground level (2m) Conc.}}$ ) were obtained by normalizing all VOC concentrations to the concentrations observed at the 2-m height of Tower 1 (T1-2 at Farm 1 and T1-1 at Farm 2) in the same experiment; this sample (T1-2) was referred to as the reference sample. Normalization allowed for comparison of the two campaigns. For VOC concentrations below the limit of detection, 0.5 of the value of the limit of detection was used for statistical analyses and figure construction. VOC levels from background samples varied significantly and were likely influenced by additional sources. These values were not used to correct the sample concentrations observed at the ventilation fans.

## Results and discussions

Composite air samples were collected at multiple heights and distances through five daytime and five nighttime field experiments outside one house at both poultry farms. Fourteen samples (including one background) were collected for two hours on three 10-m sampling towers at Farm 1, and 13 samples at Farm 2 (**Fig 1**). Samples were analyzed for nine C<sub>2</sub> – C<sub>6</sub> VOCs (molar mass < 90 g mol<sup>-1</sup>): propene, methanol, acetone, ethanol, acetonitrile, hexane, propanol, butanol, and butanal. VOC concentrations from each experiment at both Farms can be found in **SI Table 2**.

During the ten sampling time periods at Farm 1, the daytime and nighttime (mean ± standard deviation) temperatures were 27.2 ± 1.5°C and 22.0 ± 2.1°C; atmospheric pressures were 0.89 ± 0.01 and 0.94 ± 0.01 atm; relative humidity was 49% ± 4% and 67% ± 3%, calm percentages (wind speed < 0.5m/s) were 52% ± 30% and 100% ± 0%, respectively. (**SI, Table 1**). At Farm 2, daytime and nighttime (mean ± standard deviation) temperatures were 20.2 ± 4.4°C and 22.2 ± 3.0°C; atmospheric pressures were 0.97 ± 0.02 and 0.92 ± 0.03 atm; relative humidity was 73% ± 17% and 76% ± 13%, calm percentages (wind speed < 0.5m/s) were 25% ± 30% and 46% ± 38% during sampling time, respectively (**SI, Table 2**).

### Methanol

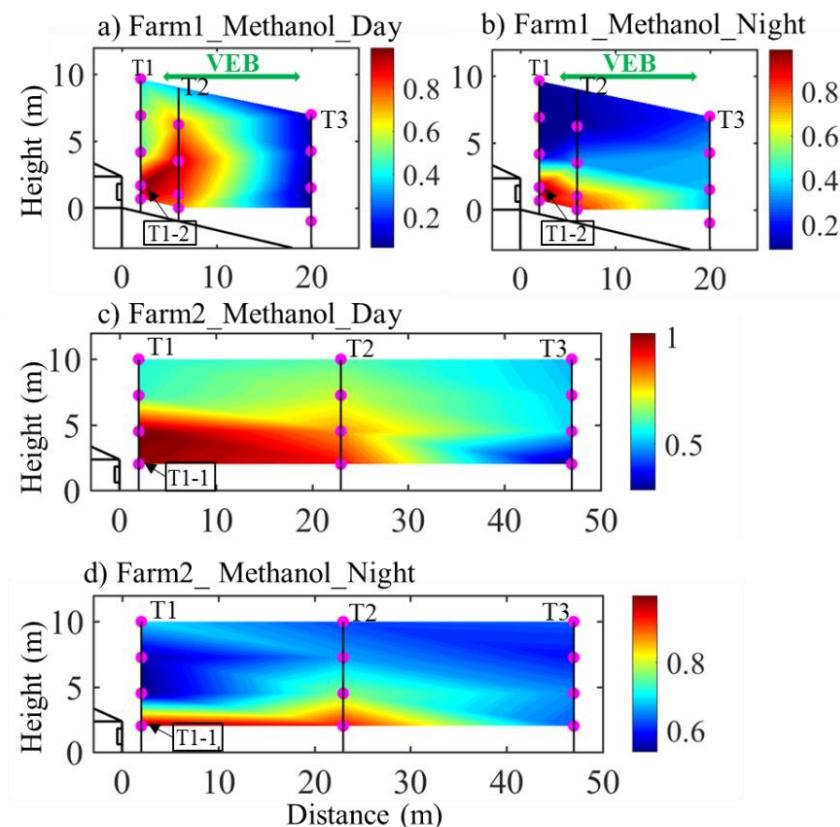
Of the VOCs measured in this study, the most abundant VOC observed at both farms was methanol, and all samples contained detectable levels of methanol. The average methanol concentration was significantly larger than all other measured VOCs ( $p < 0.05$ ). For Farm 1 at ground level (2-m), the average methanol concentrations (ranges) were 182 ug m<sup>-3</sup> (128 - 226 μg m<sup>-3</sup>) at T1 and 47 ug m<sup>-3</sup> (12 -

110  $\mu\text{g m}^{-3}$ ) at T3 during the day, and 207  $\mu\text{g m}^{-3}$  (174 - 254  $\mu\text{g m}^{-3}$ ) and 76  $\mu\text{g m}^{-3}$  (48 - 112  $\mu\text{g m}^{-3}$ ). At Farm 2, 2-m ground level, average methanol concentrations were 116  $\mu\text{g m}^{-3}$  (96 - 138  $\mu\text{g m}^{-3}$ ) and 56  $\mu\text{g m}^{-3}$  (17 - 127  $\mu\text{g m}^{-3}$ ) at T1 and T2 respectively, and were 106  $\mu\text{g m}^{-3}$  (69 - 137  $\mu\text{g m}^{-3}$ ) and 83  $\mu\text{g m}^{-3}$  (37 - 124  $\mu\text{g m}^{-3}$ ) for nighttime. The difference in average methanol concentrations between the two poultry houses may be due to the different house managements and temperatures. Higher temperatures tend to promote higher VOC emissions from the poultry houses.

To compare the VOC emissions between experiments, relative concentration was used due to the wide range of concentration levels. Relative concentrations were plotted as a function of distance to the primary ventilation fan and the height for each experiment at both farms (**Fig 2; SI Figs. 3 & 4**). A representative relative methanol concentration gradient during daytime at Farm 1 shows the emission plume originating from the ventilation fan (**Fig. 2a**). The plume appeared to be Gaussian, matching previous studies (Willis et al., 2017a, 2017b). The plume lofted upwards in the relatively short distance from T1 to T2 (< 5 m), most likely due to the presence of the VEB. **Fig. 2c** shows an extended plume of more than 40 m, while the plume in **Fig 2a** was less than 20 m. Thus, the VEB prevented the VOC plume from moving far beyond the poultry house.

A typical methanol emission pattern during the nighttime at Farm 1 is shown in **Fig. 2b**. It is somewhat similar to the emission plume that emanated from the ventilation fan during the day, however, the plume height was much lower and reached further into the VEB. This is not unexpected as much calmer wind conditions and lower temperatures during the nighttime can create a nocturnal radiation

inversion. The ground-level methanol plumes were trapped under the warmer air giving rise to the suppressed and extended plume shape. Similar to **Fig 2b**, the nighttime plume of Farm 2 shown in **Fig. 2d** is suppressed and somewhat extended.



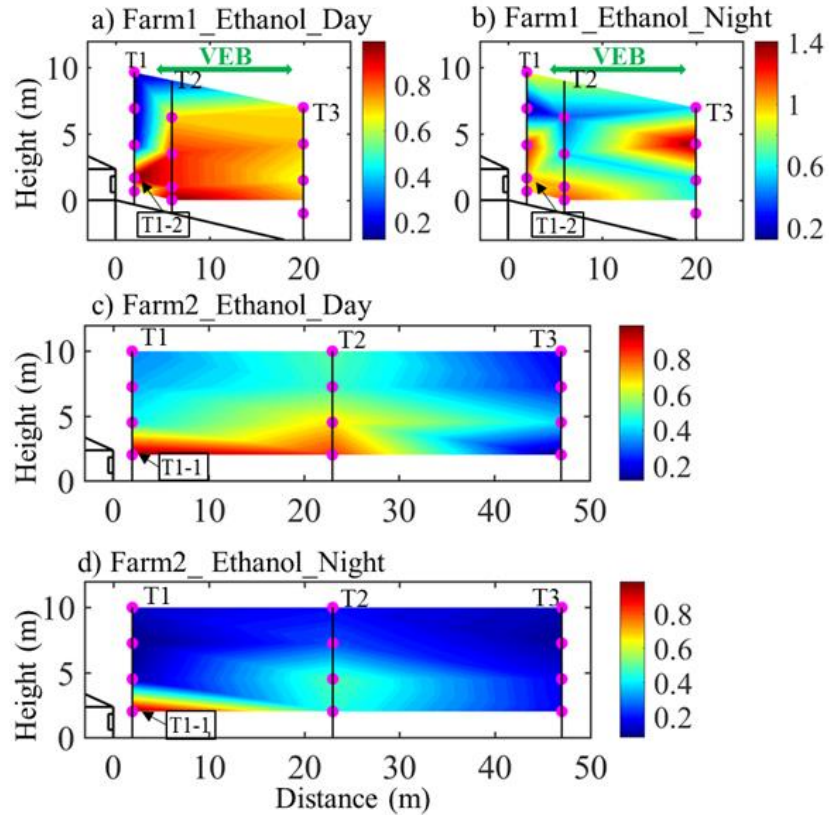
**Figure 2.** Relative methanol concentration gradient a) daytime at Farm 1; b) nighttime at Farm 1; c) daytime at Farm 2; d) nighttime at Farm 2. All concentrations were normalized by concentration of 2-m height sampler on Tower 1 (T1-2 for Farm 1 and T1-1 for Farm 2) from the same experiment.

At ground-level (2-m height), methanol concentrations at Farm 1 decreased by 75% ( $\pm 16\%$ ) over the span of 18 m (T1 to T3) in the day experiments and by 63% ( $\pm 8\%$ ) in the night experiments, whereas, at Farm 2, methanol concentrations decreased by 47% ( $\pm 39\%$ ) and 16% ( $\pm 22\%$ ) over 21 m (T1 to T2) for day and night experiments, respectively. Although, environmental conditions were not exactly the same, these data provide additional evidence that the VEB impeded VOC transport.

## Ethanol and acetone

Ethanol and acetone shared very similar emission patterns at both farms. The relative ethanol concentrations were plotted as a function of distance from the primary ventilation fan and height for each experiment (**Fig. 3, SI Figs. 5, 6, 7, & 8**). Results showed that ethanol was emitted from the poultry house (**Fig. 3a**). Statistical analysis demonstrated that the relative acetone and ethanol concentration profile were not statistically significantly different from methanol concentration profile ( $p$ -value > 0.05). For the nocturnal ethanol emissions at both farms (**Figs. 3b and 3d**), the ethanol plume was suppressed which is consistent with the inversion pattern observed with methanol. However, high background acetone and ethanol levels at some of experiments in both farms suggested additional sources. Dairy and swine facilities have been reported as significant contributors for both ethanol and acetone emissions (Blunden et al., 2005; Filipy et al., 2006), and these type of facilities are within visual distance at both farms.



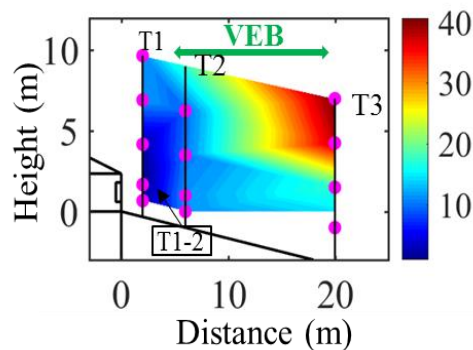


**Figure 3.** Ethanol relative concentration gradient: a) daytime at Farm 1; b) nighttime at Farm 1; c) daytime at Farm 2; d) nighttime Farm 2. All concentrations were normalized by concentration of 2-m height sampler on Tower 1 (T1-2 for Farm 1 and T1-1 for Farm 2) from the same experiment.

#### Other VOCs

Acetonitrile, propanol, butanol, hexane, and propene were detected in 40% of the gas samples collected at Farm 1 (4 experiments), and in less than 5% of the gas samples from Farm 2. For these five VOCs, the ground-level (2-m height) VOC concentrations in front of the ventilation fan were significantly lower ( $p < 0.05$ ) than at T3 location (20-m distance, behind VEBs) at Farm 1. The relative concentration changes as a function of distance for butanol at Farm 1 are shown in **Fig 4**. All other VOCs emission patterns are shown in **SI Fig.9**. Butanol concentrations in front of the

poultry ventilation fans were the lowest, whereas larger concentrations were observed much higher at T3 indicating that the poultry house is not the primary source for this compound. Additionally, background samples showed the largest concentrations levels of these VOCs in 2 experiments at Farm 1. Acetonitrile, propanol, hexane, and propene had other dominant emission sources as well.



**Figure 4.** Typical butanol relative concentration gradient at Farm 1. All concentrations were normalized by sample T1-2 (2m height on Tower 1) concentration from the same experiment.

Dimethyl sulfide, carbon disulfide, dimethyl disulfide, toluene, hexanal, and nonanal, have been reported as malodorous VOCs and have been detected inside poultry houses ((Blunden et al., 2005; Filipy et al., 2006; Trabue et al., 2010). They were also identified in the collected air samples from both farms, but were not quantified against standards. Carbon disulfide, dimethyl sulfide, and dimethyl disulfide had very similar emission patterns as methanol (**Fig. 2**), indicating that the poultry houses were the emission source of these compounds. Hexanal exhibited similar patterns as ethanol and acetone (**Fig. 3**) suggesting that broiler houses are an emission source, but not the only source. Nonanal and toluene presented same

concentration spatial changes as butanol (**Fig. 4**), suggesting that other emission sources other than poultry farms are dominant.

#### Ozone formation potential

VOCs have a wide range of hydroxyl radical reactivity which is a function of their chemical properties. Propylene-equivalent concentration (Prop-Equiv) is one approach (Chameides et al., 1992) to measure the relative VOC reactivity based on a scale normalized to propene reactivity:

$$\text{Prop-Equiv } (j) = \text{Conc } (j) \times k_{OH} (j)/k_{OH} (\text{propene}) \quad (\text{Equation 1})$$

where  $\text{Conc } (j)$  is the averaged daytime concentration of the VOC  $j$  and  $k_{OH} (j)$  and  $k_{OH} (\text{propene})$  are the rate constants at 298 K for the gas-phase reactions of VOC and the hydroxyl radical (Atkinson, 1989).

The ozone formation potential (OFP) of a VOC is a function of its concentration and its maximum incremental reactivity (MIR) (Carter, 1994). MIR, which is used by California Air Resources Board for regulation applications of VOCs associated with ground-level ozone formation, assumes a modeled scenario in which the NO<sub>x</sub> level yields the highest incremental reactivity of the mixture of reactive organic gases (CARB, 2009; Carter, 1998). The MIR coefficient is in units of grams O<sub>3</sub> per gram VOC (Carter, 1994, 2010).

$$\text{OFP } (j) = \text{Conc. } (j) \times \text{MIR coefficient } (j) \quad (\text{Equation 2})$$

**Table 1** shows the VOC reactivity (Prop-Equiv) of methanol, ethanol, and acetone as well as their respective ozone formation potential (OFP) values and MIR

coefficients using the daytime ground-level (2-m height) VOC concentrations from both farms. The largest potential contributor to ozone formation is methanol followed by ethanol and acetone. Direct comparison of the Prop-Equiv and OFP between the two farms is not appropriate, since data were collected under different environmental conditions, and Prop-Equiv and OFP are calculated using actual not relative concentrations. However, the change in the Prop-Equiv and the OFP at each farm as a function of distance (2 m and 20m) are substantially different. For methanol, the OFP decreased  $75\% \pm 16\%$  at Farm 1 and  $52\% \pm 40\%$  at Farm 2. These calculations suggest that using VEBs may be a useful practice in reducing potential ozone formation due to VOCs emitted from poultry houses. Finally, the increases in OFP for ethanol and acetone as a function of increasing distance from the source at Farm 1 again indicate that additional sources for these compounds exist.

**Table 1.** Reactivities of poultry emitted VOCs at 2-m height

VOCs	Distance (m)	Avg. Conc. ( $\mu\text{g}/\text{m}^3$ )		$10^{-12} * k_{OH}^b$ ( $\text{cm}^3 \text{mole}^{-1} \text{s}^{-1}$ )	MIR <sup>c</sup>	Prop-Equiv (ppbc)		OFP ( $\mu\text{g}/\text{m}^3$ )	
		Farm 1	Farm 2			Farm 1	Farm 2	Farm 1	Farm 2
Methanol	2m	182 ± 41	116 ± 20	1.06	0.67	5.7 ± 1.3	3.6 ± 0.6	93 ± 21	59 ± 10
	~ 20m <sup>a</sup>	47 ± 37	36 ± 29			1.5 ± 1.2	1.7 ± 0.5	24 ± 19	29 ± 25
Ethanol	2m	30 ± 14	50 ± 10	3.74	1.53	2.3 ± 0.9	3.8 ± 0.1	24 ± 3.4	41 ± 3.0
	~ 20m <sup>a</sup>	33 ± 54	16 ± 14			2.5 ± 2.6	1.6 ± 0.1	27 ± 10	17 ± 4.2
Acetone	2m	25 ± 11	35 ± 7	0.63	0.56	0.3 ± 0.1	0.4 ± 0.1	5.8 ± 8.9	8.3 ± 4.5
	~ 20m <sup>a</sup>	47 ± 34	17 ± 12			0.5 ± 0.5	0.2 ± 0.1	11 ± 35	4.9 ± 7.4

<sup>a</sup>Farm 1: 20-m distance to the primary fan; Farm 2: 23-m distance to the primary fan.

<sup>b</sup>Rate constant of VOC reacts with OH radical at 298K (Atkinson, 1989).

<sup>c</sup>Maximum incremental reactivity (g O<sub>3</sub> formation / g VOC) (Carter, 1994)

## Chapter 6: Conclusion

VEB showed sufficient collection efficiency for the major air pollutants emitted from the poultry house. Behind the VEB, the average reduction for TSP by 88%, for PM<sub>10</sub> by 88%, for PM<sub>2.5</sub> by 94%, for NH<sub>3</sub> by 83%.

By comparing the field-observed and model-predicted VEB collection efficiency, TSP, PM<sub>10</sub>, PM<sub>2.5</sub>, and NH<sub>3</sub> emission reduction was increased by 17%, 21%, 25% and 25% respectively.

TSP, PM<sub>10</sub>, PM<sub>2.5</sub> emissions and reduction were statistically correlated. VEB efficiency of TSP, PM<sub>10</sub> both had high correlation ( $r = 0.98$ ) and high coefficient for linear regression analysis ( $r^2 = 0.965$ ). Thus, showing the possibility to predict the PM<sub>10</sub> reduction by TSP measurements.

PM<sub>2.5</sub>, and NH<sub>3</sub> emissions were strongly correlated ( $r = 0.72, 0.55, 0.55$  for Camp 1, 2, and 3) as expected since NH<sub>3</sub> knowingly contributed to secondary PM<sub>2.5</sub>. The VEB collection efficiencies of these two pollutants were also strongly correlated ( $r = 0.66$  and  $0.59$  for day and night).

The result showed that the poultry houses were the primary emission source for methanol, ethanol, and acetone, of which were also found to have the largest ozone formation potential (OFP). Methanol contributed the most OFP as  $93 \pm 21 \mu\text{g}/\text{m}^3$  and  $59 \pm 10 \mu\text{g}/\text{m}^3$  in front of the tunnel fan of two different poultry houses. A substantial decrease in the OFP for methanol was observed as a function of distance from the poultry house equipped with VEB. These results suggest that VEBs can provide some control on the VOCs emitted from poultry production.

## Appendices A: Chapter 3 supplementary information

### Equation 1: Gaussian Plume model Equation

$$C(x, y, z) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) \left[ \exp\left(\frac{-(z+h)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z-h)^2}{2\sigma_z^2}\right) \right]$$

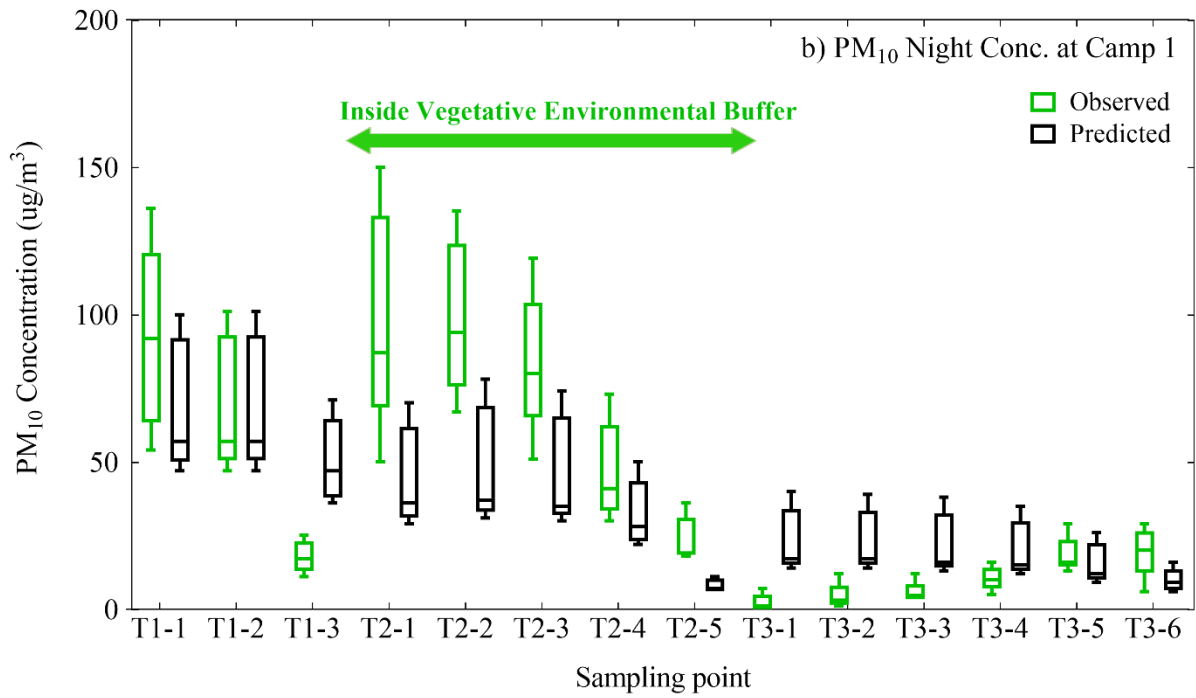
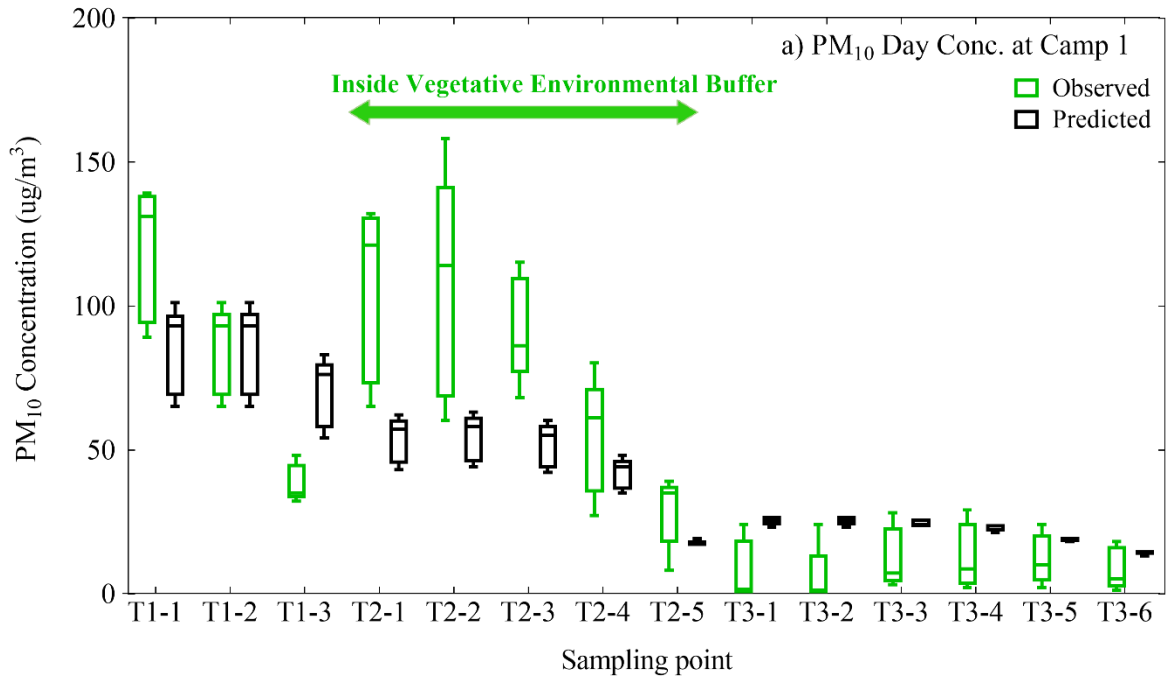
where  $x, y$  and  $z$  were the downwind crosswind and vertical coordinates, and  $h$  was releasing height from the ground.  $Q$  was source strength,  $u$  was wind speed.  $\sigma_y$  and  $\sigma_z$  were the standard deviation of the distribution concentration in  $y$  and  $z$  axis, and they were related to meteorological condition. This equation revealed the concentration was a function of a given location. Term  $\exp\left(\frac{-(z+h)^2}{2\sigma_z^2}\right)$  refers to the reflection from the ground.

Gaussian Plume model general assumptions:

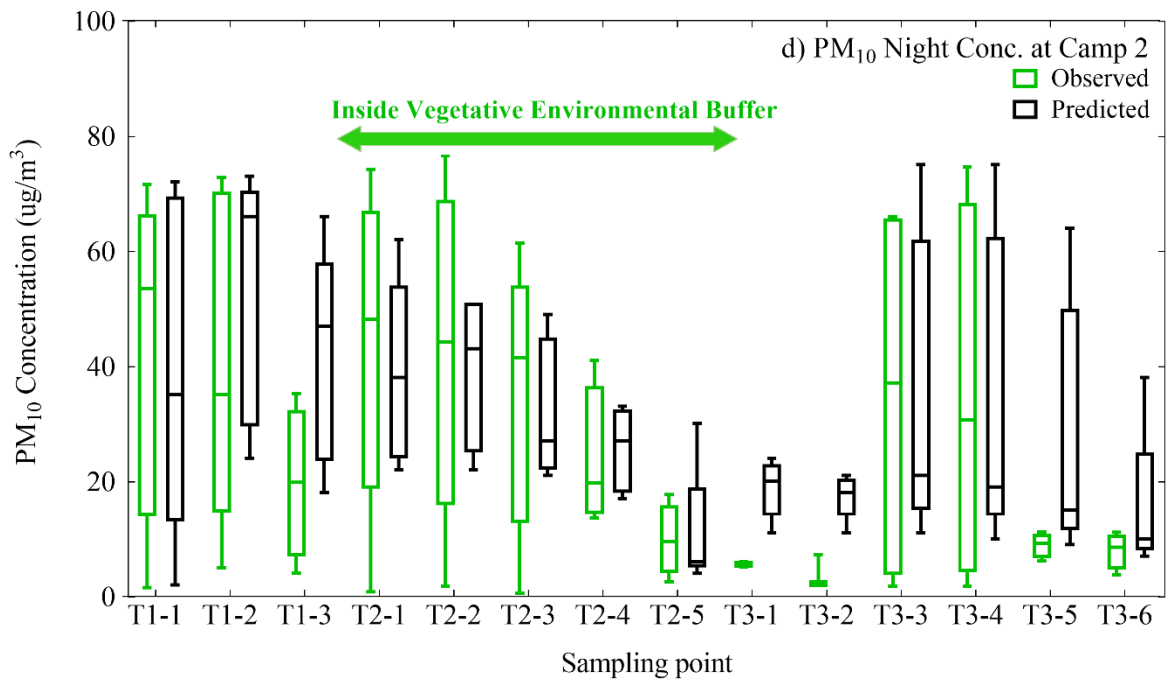
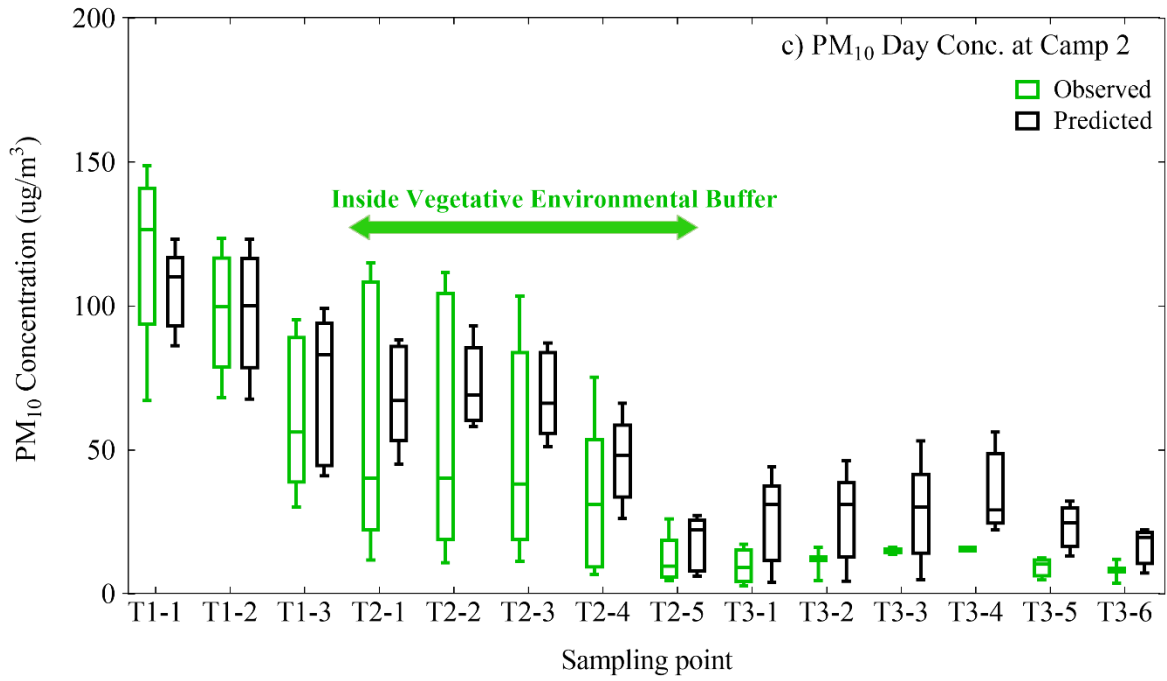
- the pollutant concentration was normally distributed both horizontally and vertically;
- steady state meteorological condition within an hour;
- source strength and position were constant;
- no PM deposition occurred, mass was conserved.

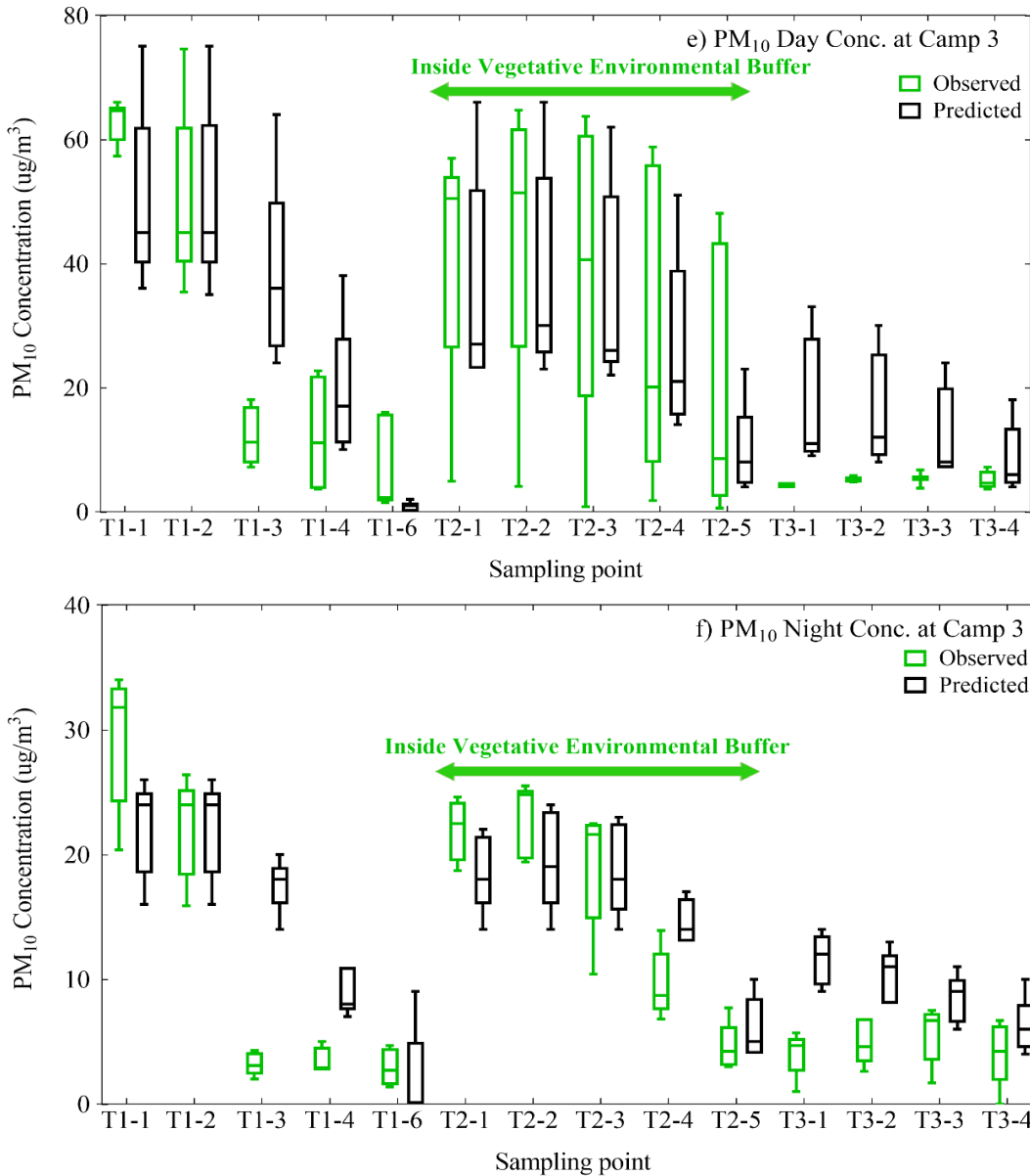
Additional assumptions for poultry emission stimulation application:

- A virtual point source was created 6.6 m directly behind the tunnel to avoid considering fan as an area source;
- Mechanical ventilation fan had the dominant wind direction;
- Superposition principle was applied to sum up multiple fan emissions at one sampling point.

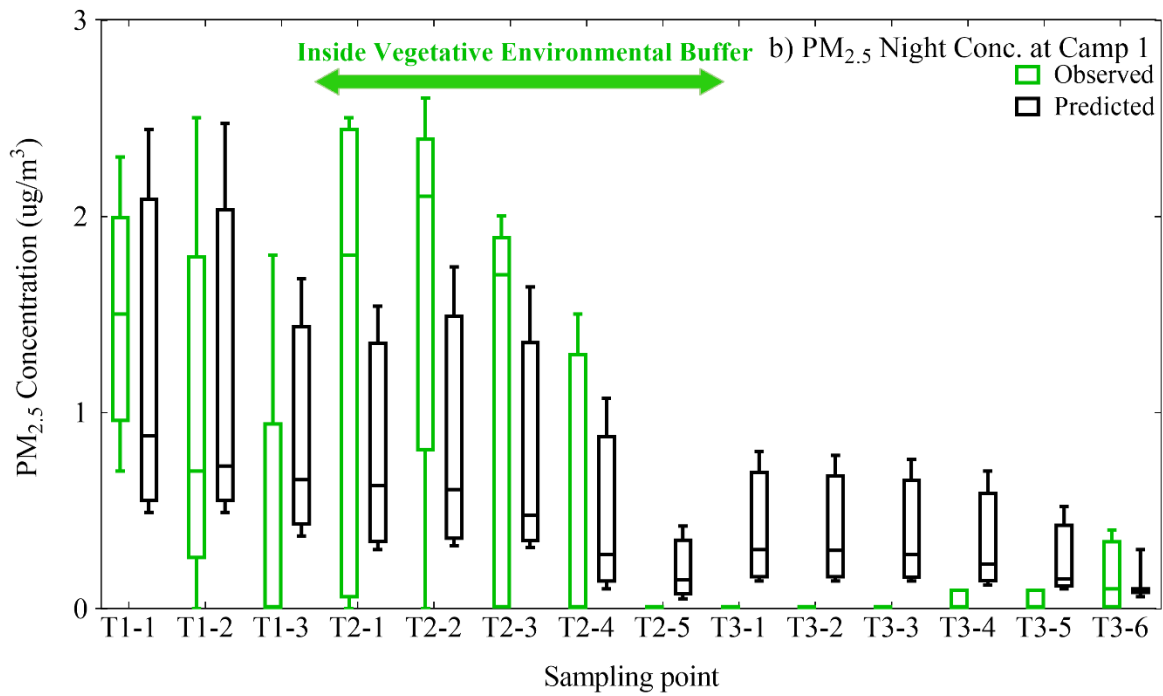
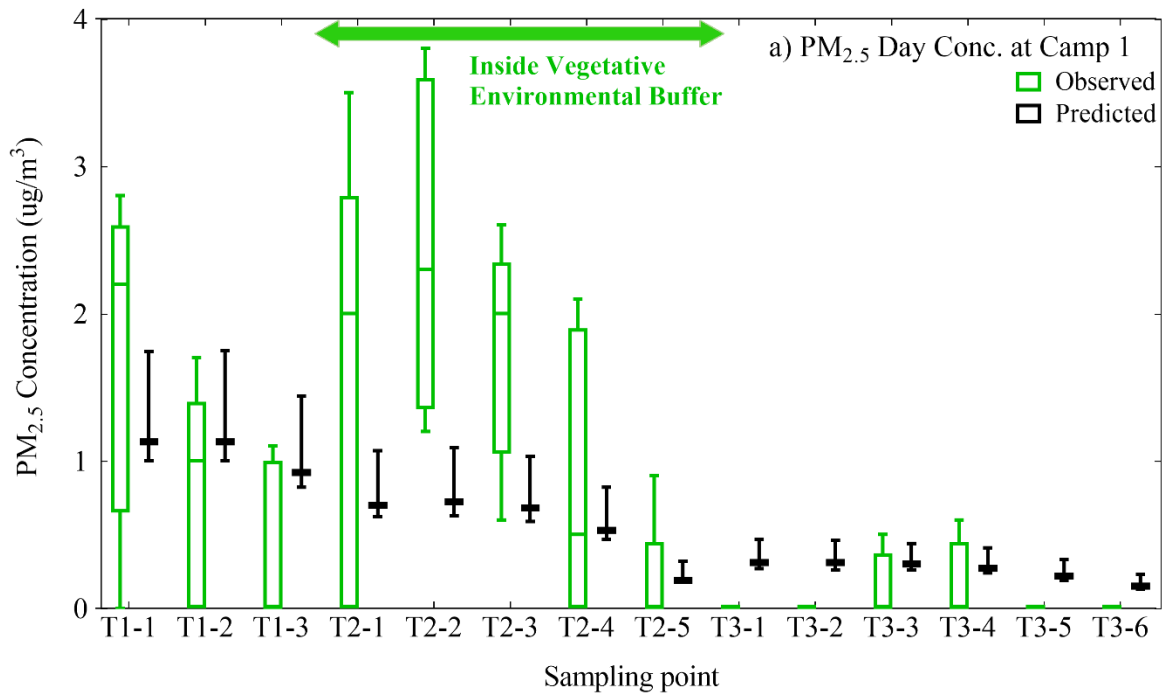


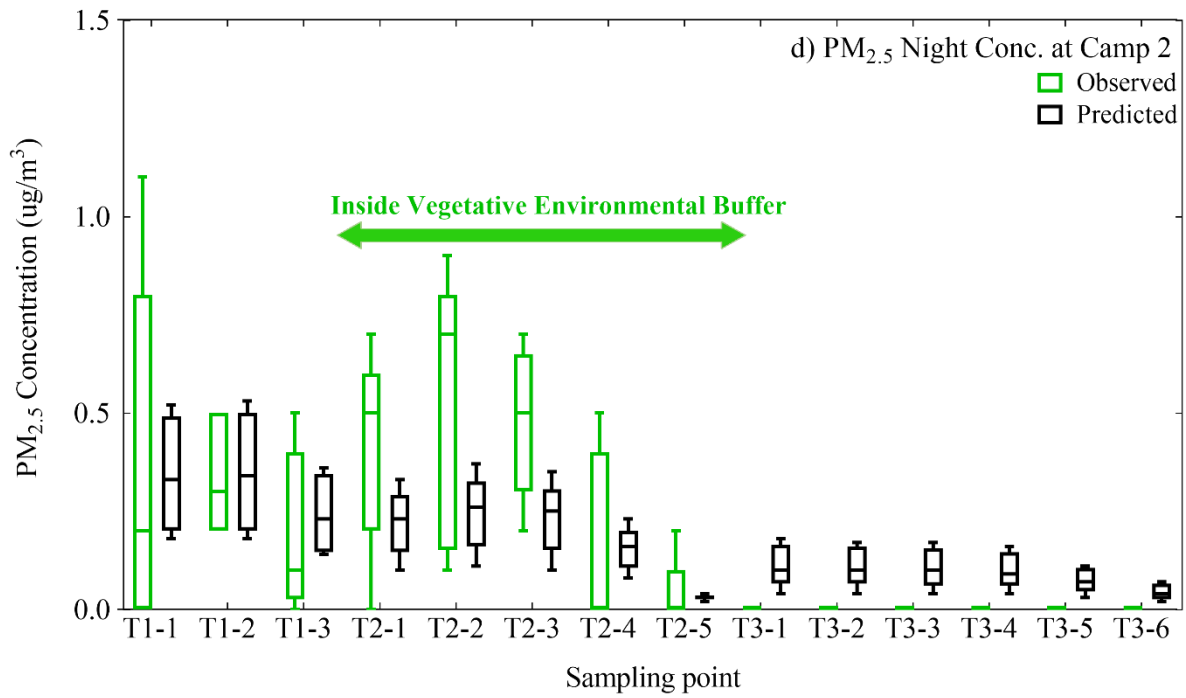
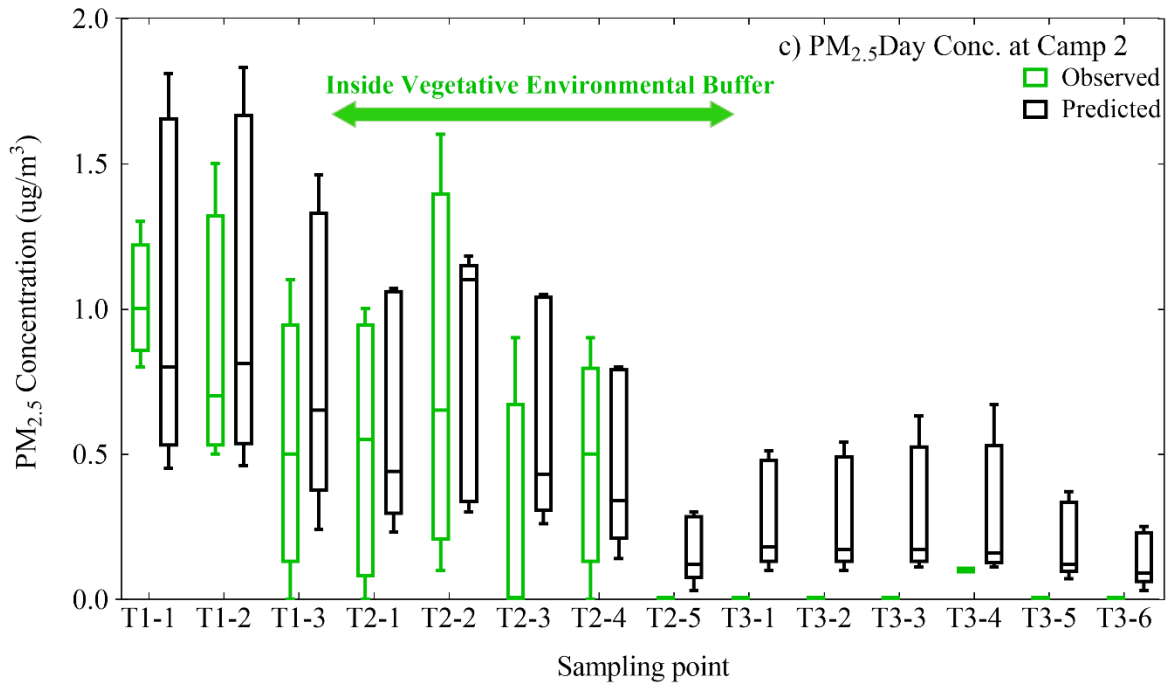


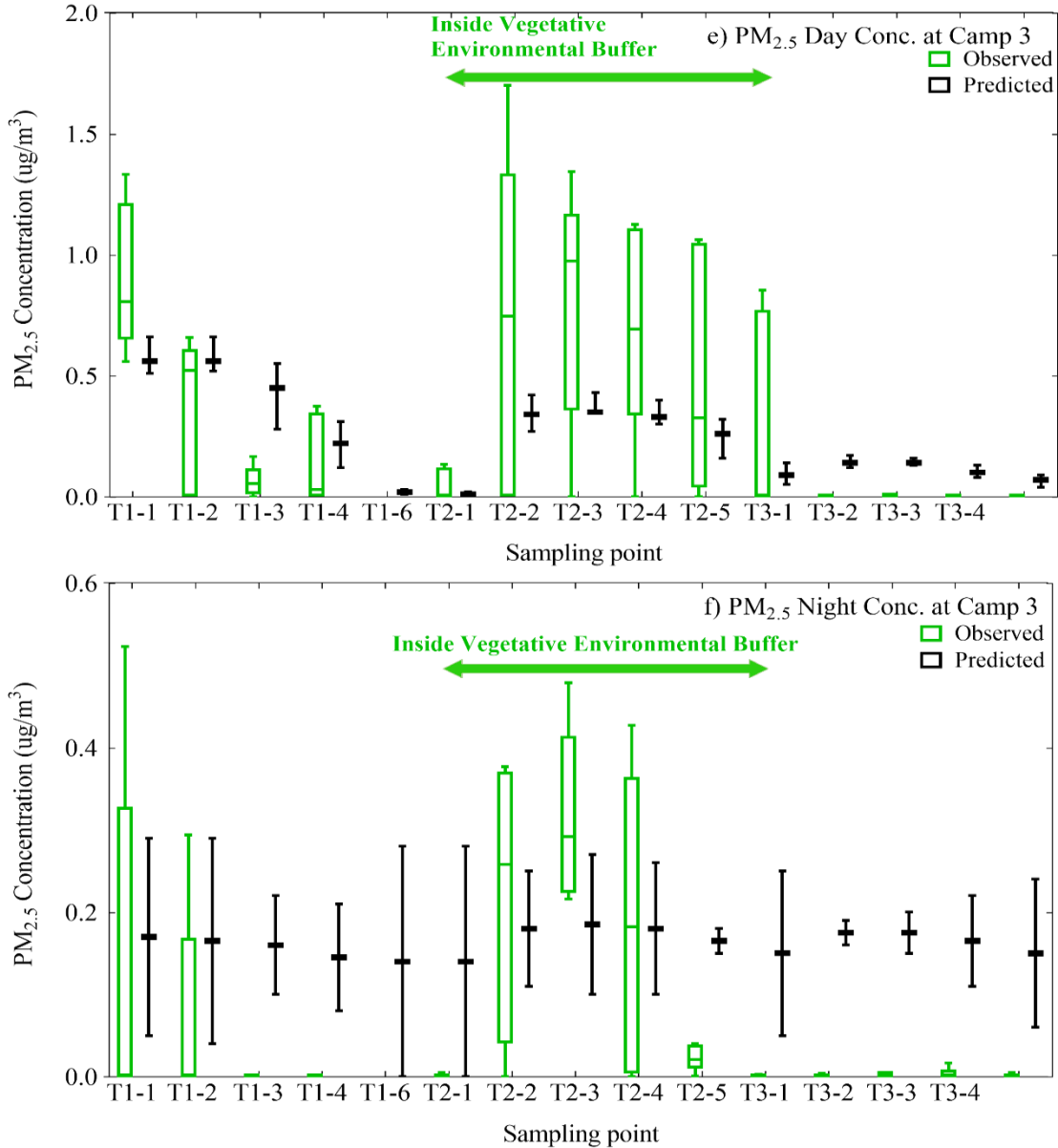




**Figure 1.** Tukey box-plots of observed and predicted  $PM_{10}$  concentrations at different sampling points. Observed  $PM_{10}$  concentration (green) were from five day/nighttime sampling experiments of each campaign, and predicted  $PM_{10}$  (black) concentrations were from model estimation with the same meteorological conditions as the same sampling period. a) Diurnal observed and predicted  $PM_{10}$  concentrations at Camp 1; b) Nocturnal observed and predicted  $PM_{10}$  concentrations at Camp 1; c) Diurnal observed and predicted  $PM_{10}$  concentrations at Camp 2; d) Nocturnal observed and predicted  $PM_{10}$  concentrations at Camp 2; e) Diurnal observed and predicted  $PM_{10}$  concentrations at Camp 3; and f) Nocturnal observed and predicted  $PM_{10}$  concentrations at Camp 3. Sampling points were shown in the **Fig. 2**. Tower 1 was 2 m away from the tunnel fan; Tower 2 (inside the VEB) was 6 m away from the tunnel fan; Tower 3 was 20 m away from the tunnel fan







**SI Figure 2.** Tukey box-plots of observed and predicted PM<sub>2.5</sub> concentrations at different sampling points. Observed PM<sub>2.5</sub> concentration (green) were from five day/nighttime sampling experiments of each campaign, and predicted PM<sub>2.5</sub> (black) concentrations were from model estimation with the same meteorological conditions as the same sampling period. a) Diurnal observed and predicted PM<sub>2.5</sub> concentrations at Camp 1; b) Nocturnal observed and predicted PM<sub>2.5</sub> concentrations at Camp 1; c) Diurnal observed and predicted PM<sub>2.5</sub> concentrations at Camp 2; d) Nocturnal observed and predicted PM<sub>2.5</sub> concentrations at Camp 2; e) Diurnal observed and predicted PM<sub>2.5</sub> concentrations at Camp 3; and f) Nocturnal observed and predicted PM<sub>2.5</sub> concentrations at Camp 3. Sampling points were shown in the **Fig. 2**. Tower 1 was 2 m away from the tunnel fan; Tower 2 (inside the VEB) was 6 m away from the tunnel fan; Tower 3 was 20 m away from the tunnel fan

**Table 2.** Observed and predicted PM concentrations from Campaign 1

<b>Campaign 1, TSP Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1243	1391	1672	1869	1796	916	1096	1496	1716	1058
T1-2	916	1076	1292	1246	1313	739	736	1068	1143	754
T1-3	543	644	535	507	684	211	295	296	353	274
T2-1	866	1146	1664	1772	1808	717	1141	1450	1625	1176
T2-2	848	1309	1615	1770	1863	979	1187	1547	1607	1211
T2-3	851	1335	1364	1360	1679	867	1059	1212	1177	1117
T2-4	641	1005	477	990	1289	549	607	771	1086	452
T2-5	429	564	224	538	742	324	447	338	573	382
T3-1	34	33	366	110	81	52	46	151	81	63
T3-2	37	34	400	133	96	70	64	181	111	89
T3-3	39	32	429	150	109	111	96	225	158	134
T3-4	42	38	465	183	124	163	153	292	253	212
T3-5	50	39	380	208	140	248	236	401	452	357
T3-6	50	43	273	198	116	233	261	411	497	330

<b>Campaign 1, TSP Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	912	1072	1287	1241	1307	733	733	1056	1132	748
T1-2	916	1076	1292	1246	1313	739	736	1068	1143	754
T1-3	749	897	1066	1030	1072	571	603	734	819	574
T2-1	575	678	798	774	828	463	463	674	806	474
T2-2	590	686	811	786	849	493	475	757	891	509
T2-3	563	653	772	748	809	471	454	716	846	487
T2-4	447	529	616	598	640	354	361	472	584	362
T2-5	180	232	250	246	247	118	148	92	140	120
T3-1	274	316	360	350	388	238	223	357	476	250
T3-2	269	311	354	344	380	233	219	351	467	246
T3-3	261	302	343	333	368	226	213	341	453	238
T3-4	244	283	319	311	342	210	199	316	419	222
T3-5	199	234	259	253	276	169	163	238	321	179
T3-6	148	178	190	186	199	120	122	145	206	129

<b>Campaign 1, PM<sub>10</sub> Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	89	98	138	139	131	54	92	106	136	73
T1-2	65	72	101	93	94	47	57	85	101	54
T1-3	34	42	35	32	48	17	21	15	25	11
T2-1	65	80	121	130	132	50	87	117	150	87
T2-2	60	76	114	125	158	67	84	113	135	94
T2-3	68	85	86	105	115	51	79	89	119	80
T2-4	43	63	27	61	80	37	41	52	73	30
T2-5	27	36	8	35	39	18	26	19	36	19
T3-1	0		24	3	0	1	0	7	3	0
T3-2	0	1	24	3	0	4	2	12	3	1
T3-3	3		28	8	6	5	4	12	4	4
T3-4	2		29	11	6	12	9	16	10	5
T3-5	2		24	10	10	13	16	29	16	18
T3-6	3	1	18	15	5	6	20	29	24	19

<b>Campaign 1, PM<sub>10</sub> Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	65	72	101	93	93	47	57	84	100	53
T1-2	65	72	101	93	94	47	57	85	101	54
T1-3	54	61	83	77	76	36	47	58	71	40
T2-1	43	47	62	57	59	29	36	54	70	33
T2-2	44	47	63	58	60	31	37	60	78	35
T2-3	42	45	60	55	57	30	35	57	74	34
T2-4	35	37	48	44	45	22	28	37	50	24
T2-5	17	19	18	17	17	6	11	7	10	6
T3-1	23	24	27	25	27	14	17	28	40	16
T3-2	23	24	27	25	27	14	17	28	39	16
T3-3	23	23	26	24	26	13	16	27	38	15
T3-4	21	22	24	22	24	12	15	25	35	14
T3-5	19	19	19	18	19	9	12	19	26	11
T3-6	15	15	14	13	14	6	9	11	16	7

<b>Campaign 1, PM<sub>2.5</sub> Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1.27	0.00	2.20	2.76	2.38	0.69	1.18	1.65	2.32	1.51
T1-2	1.13	0.00	1.75	1.00	0.00	0.00	0.70	2.47	1.06	0.49
T1-3	0.00	0.00	0.94	0.00	1.15	1.81	0.00	0.10	0.00	0.00
T2-1	0.04	0.00	2.06	3.49	1.95	0.00	1.81	0.12	2.40	2.45
T2-2	1.17	1.49	2.33	3.39	3.84	0.00	1.59	2.11	2.25	2.65
T2-3	0.62	1.46	1.99	2.08	2.61	0.00	0.00	1.71	1.84	2.02
T2-4	0.00	0.00	0.53	2.05	1.72	0.00	0.00	1.12	1.49	0.00
T2-5	0.00	0.00	0.00	0.00	0.92	0.00	0.00	0.00	0.00	0.01
T3-1	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T3-2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T3-3	0.00		0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T3-4	0.00		0.59	0.00	0.00	0.00	0.00	0.08	0.07	0.00
T3-5	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.06
T3-6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.32	0.12

<b>Campaign 1, PM<sub>2.5</sub> Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1.13	0.00	1.74	1.00	0.00	0.00	0.70	2.44	1.05	0.49
T1-2	1.13	0.00	1.75	1.00	0.00	0.00	0.70	2.47	1.06	0.49
T1-3	0.92	0.00	1.44	0.82	0.00	0.00	0.57	1.68	0.75	0.37
T2-1	0.70	0.00	1.07	0.62	0.00	0.00	0.43	1.54	0.74	0.30
T2-2	0.72	0.00	1.09	0.63	0.00	0.00	0.44	1.74	0.82	0.32
T2-3	0.68	0.00	1.03	0.59	0.00	0.00	0.42	1.64	0.77	0.31
T2-4	0.53	0.00	0.82	0.47	0.00	0.00	0.33	1.07	0.53	0.22
T2-5	0.19	0.00	0.32	0.18	0.00	0.00	0.12	0.17	0.10	0.05
T3-1	0.31	0.00	0.47	0.27	0.00	0.00	0.19	0.80	0.42	0.14
T3-2	0.31	0.00	0.46	0.26	0.00	0.00	0.19	0.78	0.41	0.14
T3-3	0.30	0.00	0.44	0.26	0.00	0.00	0.18	0.76	0.40	0.14
T3-4	0.27	0.00	0.41	0.24	0.00	0.00	0.17	0.70	0.37	0.12
T3-5	0.22	0.00	0.33	0.19	0.00	0.00	0.13	0.52	0.28	0.10
T3-6	0.15	0.00	0.23	0.13	0.00	0.00	0.09	0.30	0.17	0.06



**Table 3.** Observed and predicted PM concentrations from Campaign 2

<b>Campaign 2, TSP Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1768	1986	1671	1339	1667	1011	819	397	864	1033
T1-2	1709	1672	1129	850	1208	375	582	396	911	647
T1-3	1537	1265	744	572	481	157	418	300	579	214
T2-1	236	457	1333	1125	1363	975	502	644	781	902
T2-2	203	396	1425	1139	1423	0	454	589	949	1087
T2-3	236	363	1383	1105	798	563	383	522	922	560
T2-4	153	244	1068	631	497	259	229	406	719	287
T2-5	79	106	390	158	166	101	36	190	315	112
T3-1	34	30	35	33	199	94	17	41	25	73
T3-2	32	28	32	32	206	121	17	43	27	87
T3-3	31	29	32	33	224	160	17	51	30	106
T3-4	27	25	33	29	205	166	16	54	36	113
T3-5	33	30	38	27	211	182	18	100	45	157
T3-6	31	27	42	29	182	111	18	108	28	153

<b>Campaign 2, TSP Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1700	1672	1100	847	1202	370	579	392	901	640
T1-2	1709	1672	1129	850	1208	375	582	396	911	647
T1-3	1372	1352	618	707	988	262	477	287	634	456
T2-1	1007	1201	588	512	687	241	362	422	523	346
T2-2	1043	1263	758	519	704	269	373	470	585	384
T2-3	994	1182	663	494	671	255	358	446	554	364
T2-4	774	903	355	399	535	174	288	305	372	248
T2-5	290	380	105	175	229	46	136	81	79	56
T3-1	455	606	262	230	306	121	188	327	250	153
T3-2	447	638	282	226	301	120	186	323	246	150
T3-3	433	725	304	220	292	117	181	314	238	146
T3-4	403	774	305	206	275	109	172	292	221	135
T3-5	325	448	196	171	228	86	147	225	169	104
T3-6	235	318	113	130	175	59	119	145	107	67

<b>Campaign 2, PM<sub>10</sub> Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	119	149	126	111	134	71	61	26	53	83
T1-2	111	123	88	68	100	73	35	24	68	52
T1-3	95	84	46	41	30		24	16	35	15
T2-1	12	32	103	85	115	74	37	48	60	71
T2-2	11	25	98	79	112	77	30	44	61	74
T2-3	11	25	103	82	65	47	25	41	61	36
T2-4	7	10	75	40	33	16	14	23	41	20
T2-5	4	6	26	9	10	8	3	10	18	6
T3-1	6		3	4	12	5		6		4
T3-2			4	4	12	7		2	2	5
T3-3				5	14	10		2	3	8
T3-4					16	12		2	2	8
T3-5	8		5		12	10		6	2	9
T3-6			4		12	9		8	2	9

<b>Campaign 2, PM<sub>10</sub> Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	110	123	86	67	99	72	35	24	67	51
T1-2	111	123	88	68	100	73	35	24	68	52
T1-3	90	99	47	56	83	50	29	18	47	36
T2-1	67	88	45	40	60	46	22	26	38	27
T2-2	69	93	58	40	61	51	22	28	43	30
T2-3	66	87	51	38	59	49	21	27	41	29
T2-4	52	66	26	31	48	32	17	19	27	19
T2-5	22	27	6	12	25	6	8	6	4	4
T3-1	32	44	18	17	31	22	11	20	17	11
T3-2	32	46	20	16	31	21	11	20	17	11
T3-3	31	53	22	16	30	21	11	19	17	11
T3-4	29	56	22	15	29	19	10	18	15	10
T3-5	24	32	13	12	25	15	9	14	11	7
T3-6	18	22	7	8	21	9	7	10	7	4

<b>Campaign 2, PM<sub>2.5</sub> Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1.35	1.03	0.96	0.84	1.31	0.53	0.00	0.00	0.21	1.06
T1-2	1.83	1.51	0.46	0.60	0.81	0.53	0.18	0.22	0.34	0.47
T1-3	1.25	1.07	0.50	0.00	0.48		0.05	0.08	0.47	0.00
T2-1	0.07	0.00	0.30	0.85	1.02	0.54	0.00	0.38	0.46	0.67
T2-2	0.01	0.06	0.46	0.85	1.63	0.88	0.14	0.24	0.70	0.71
T2-3	0.01	0.00	0.00	0.00	0.85	0.56	0.24	0.51	0.65	0.36
T2-4	0.00	0.04	0.86	0.54	0.51	0.00	0.03	0.26	0.49	0.00
T2-5	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.15	0.00
T3-1	0.00		0.00	0.00	0.00	0.00		0.02		0.00
T3-2			0.00	0.00	0.00	0.00		0.00	0.00	0.00
T3-3				0.00	0.00	0.00		0.00	0.00	0.00
T3-4					0.05	0.00		0.00	0.00	0.00
T3-5	2.65		0.00		0.00	0.00		0.00	0.00	0.00
T3-6			0.04		0.00	0.00		0.00	0.04	0.00

<b>Campaign 2, PM<sub>2.5</sub> Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1.81	1.51	0.45	0.60	0.80	0.52	0.18	0.22	0.33	0.46
T1-2	1.83	1.51	0.46	0.60	0.81	0.53	0.18	0.22	0.34	0.47
T1-3	1.46	1.21	0.24	0.50	0.65	0.36	0.14	0.15	0.23	0.33
T2-1	1.06	1.07	0.23	0.35	0.44	0.33	0.10	0.23	0.19	0.25
T2-2	1.10	1.13	0.30	0.36	1.18	0.37	0.11	0.26	0.21	0.28
T2-3	1.04	1.05	0.26	0.34	0.43	0.35	0.10	0.25	0.20	0.26
T2-4	0.80	0.79	0.14	0.27	0.34	0.23	0.08	0.16	0.13	0.17
T2-5	0.28	0.30	0.03	0.11	0.12	0.04	0.03	0.03	0.02	0.03
T3-1	0.46	0.51	0.10	0.15	0.18	0.15	0.04	0.18	0.09	0.10
T3-2	0.45	0.54	0.10	0.15	0.17	0.15	0.04	0.17	0.09	0.10
T3-3	0.43	0.63	0.11	0.14	0.17	0.14	0.04	0.17	0.08	0.10
T3-4	0.40	0.67	0.11	0.13	0.16	0.13	0.04	0.16	0.08	0.09
T3-5	0.31	0.37	0.07	0.11	0.12	0.10	0.03	0.11	0.06	0.07
T3-6	0.22	0.25	0.03	0.08	0.09	0.06	0.02	0.07	0.03	0.04

**Table 4.** Observed and predicted PM concentrations from Campaign 3

<b>Campaign 3, TSP Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1014	1167	1054	1030	909	558	496	506	498	413
T1-2	1127	762	675	724	723	508	359	409	373	352
T1-3	314	207	140	302	297	86	50	48	64	83
T1-4	236	71	84	399	374	75	44	44	65	99
T1-6	31	30	58	291	281	46	27	35	61	102
T2-1	102	892	862	831	853	356	438	393	390	1
T2-2	106	894	885	1136	1002	381	434	401	438	464
T2-3	54	630	727	1150	1128	305	369	329	390	442
T2-4	71	293	407	1022	920	194	177	142	191	268
T2-5	32	88	193	790	661	84	75	57	90	154
T3-1	16	99	94	30	29	49	102	74	107	118
T3-2	20	105	115	30	32	70	124	78	115	140
T3-3	16	106	115	33	33	66	125	83	130	159
T3-4	16	83	94	34	32	46	78	74	108	130

<b>Campaign 3, TSP Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1134	755	680	704	721	504	361	406	371	350
T1-2	1127	762	675	724	723	508	359	409	373	352
T1-3	964	554	563	403	587	391	308	318	288	278
T1-4	585	201	326	187	300	168	190	138	126	135
T1-6	50	14	35	34	36	31	23	13	21	47
T2-1	997	585	439	382	444	436	318	365	280	270
T2-2	993	650	443	498	458	468	317	387	298	286
T2-3	940	615	420	430	437	447	300	369	284	275
T2-4	770	414	338	242	346	331	247	278	214	213
T2-5	370	94	159	96	143	106	123	90	73	91
T3-1	510	368	189	191	204	287	166	220	160	166
T3-2	464	333	173	215	186	273	152	197	144	153
T3-3	385	249	144	136	153	202	127	155	115	128
T3-4	292	148	109	86	115	136	98	107	82	100

<b>Campaign 3, PM<sub>10</sub> Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	65	66	62	65	57	33	32	28	34	20
T1-2	75	50	35	45	45	26	21	24	24	16
T1-3	8	11	7	16	18	2	3	3	4	4
T1-4	11	4	4	23	21	3	3	3	4	5
T1-6	2	2	2	16	16	2	1	3	4	5
T2-1	5	57	48	51	51	19	25	22	23	
T2-2	4	51	49	65	59	19	25	20	25	25
T2-3	1	36	41	58	64	10	22	19	23	22
T2-4	2	14	20	59	53	8	9	7	10	14
T2-5	1	4	9	48	39	3	4	3	5	8
T3-1		4	4			1	6	5	4	5
T3-2		5	6		5	3	7	4	5	7
T3-3		5	7		4	2	7	5	7	7
T3-4		4	5	7	4	0	4	4	6	7

<b>Campaign 3, PM<sub>10</sub> Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	75	49	36	44	45	26	21	24	24	16
T1-2	75	50	35	45	45	26	21	24	24	16
T1-3	64	36	29	24	36	20	18	18	18	14
T1-4	38	12	17	10	18	8	11	8	7	11
T1-6	2	0	1	0	1	0	1	0	0	9
T2-1	66	38	23	23	27	22	18	21	18	14
T2-2	66	42	23	30	28	24	18	23	19	14
T2-3	62	40	22	26	26	23	17	22	18	14
T2-4	51	27	17	14	21	17	14	16	13	13
T2-5	23	5	8	4	8	4	7	5	4	10
T3-1	33	23	9	10	11	14	9	13	10	12
T3-2	30	21	8	12	10	13	8	11	8	11
T3-3	24	16	7	7	8	9	7	9	6	11
T3-4	18	9	5	4	6	6	5	6	4	10

<b>Campaign 3, PM<sub>2.5</sub> Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1.09	0.56	1.33	0.74	0.81	0.00	0.00	0.52	0.00	0.13
T1-2	0.00	0.00	0.66	0.52	0.56	0.29	0.00	0.00	0.00	0.04
T1-3	0.07	0.06	0.02	0.17	0.00	0.00	0.00	0.00	0.00	0.00
T1-4	0.03	0.00	0.00	0.37	0.32	0.00	0.00	0.00	0.00	0.00
T1-6	0.00	0.00	0.00	0.13	0.11	0.00	0.00	0.01	0.00	0.00
T2-1	0.00	0.97	0.75	1.70	0.00	0.16	0.00	0.38	0.35	
T2-2	0.00	0.97	1.34	0.71	1.00	0.22	0.29	0.35	0.48	0.23
T2-3	0.00	0.69	0.67	1.09	1.13	0.01	0.00	0.30	0.43	0.18
T2-4	0.00	0.08	0.33	1.04	1.06	0.00	0.02	0.02	0.04	0.04
T2-5	0.00	0.00	0.00	0.85	0.69	0.00	0.00	0.00	0.00	0.00
T3-1		0.00	0.00			0.00	0.00	0.00	0.00	0.00
T3-2		0.00	0.01		0.00	0.00	0.01	0.00	0.00	0.01
T3-3		0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.02
T3-4		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01

<b>Campaign 3, PM<sub>2.5</sub> Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	0.00	0.00	0.66	0.51	0.56	0.29	0.00	0.00	0.00	0.04
T1-2	0.00	0.00	0.66	0.52	0.56	0.29	0.00	0.00	0.00	0.04
T1-3	0.00	0.00	0.55	0.28	0.45	0.22	0.00	0.00	0.00	0.03
T1-4	0.00	0.00	0.31	0.12	0.22	0.08	0.00	0.00	0.00	0.01
T1-6	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00
T2-1	0.00	0.00	0.42	0.27	0.34	0.25	0.00	0.00	0.00	0.03
T2-2	0.00	0.00	0.43	0.35	0.35	0.27	0.00	0.00	0.00	0.03
T2-3	0.00	0.00	0.40	0.30	0.33	0.26	0.00	0.00	0.00	0.03
T2-4	0.00	0.00	0.32	0.16	0.26	0.18	0.00	0.00	0.00	0.02
T2-5	0.00	0.00	0.14	0.05	0.09	0.05	0.00	0.00	0.00	0.01
T3-1	0.00	0.00	0.17	0.12	0.14	0.16	0.00	0.00	0.00	0.02
T3-2	0.00	0.00	0.16	0.14	0.13	0.15	0.00	0.00	0.00	0.02
T3-3	0.00	0.00	0.13	0.08	0.10	0.11	0.00	0.00	0.00	0.01
T3-4	0.00	0.00	0.09	0.04	0.07	0.06	0.00	0.00	0.00	0.01

## Appendices B: Chapter 4 supplementary information

### Equation 1: Gaussian Plume model Equation

$$C(x, y, z) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) \left[ \exp\left(\frac{-(z+h)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z-h)^2}{2\sigma_z^2}\right) \right]$$

where  $x, y$  and  $z$  were the downwind crosswind and vertical coordinates, and  $h$  was releasing height from the ground.  $Q$  was source strength,  $u$  was wind speed.  $\sigma_y$  and  $\sigma_z$  were the standard deviation of the distribution concentration in  $y$  and  $z$  axis, and they were related to meteorological condition. This equation revealed the concentration was a function of a given location. Term  $\exp\left(\frac{-(z+h)^2}{2\sigma_z^2}\right)$  refers to the reflection from the ground.

Gaussian Plume model general assumptions:

- the pollutant concentration was normally distributed both horizontally and vertically;
- steady state meteorological condition within an hour;
- source strength and position were constant;
- no PM deposition occurred, mass was conserved.

Additional assumptions for poultry emission stimulation application:

- A virtual point source was created 6.6 m directly behind the tunnel to avoid considering fan as an area source;
- Mechanical ventilation fan had the dominant wind direction;
- Superposition principle was applied to sum up multiple fan emissions at one sampling point.

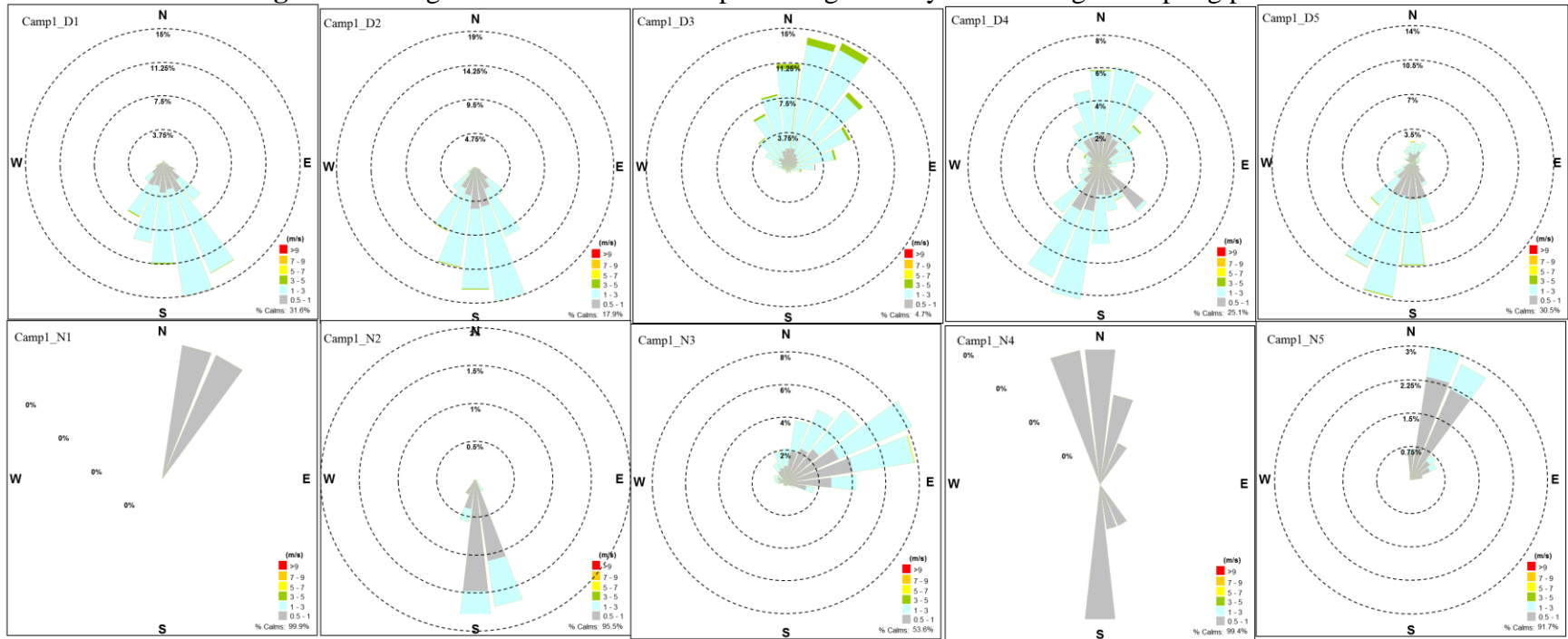
**Table 1.** Ambient wind speed and calm condition<sup>a</sup>

	Ambient Wind Speed (m/s)		Calm % <sup>a</sup>	
	Day	Night	Day	Night
Camp 1	1.1 (0.28)	0.4 (0.17)	28% (11%)	88% (20%)
Camp 2	1.5 (0.33)	0.9 (0.46)	33% (8%)	43% (30%)
Camp 3	1.5 (0.26)	0.4 (0.19)	26% (7%)	68% (35%)

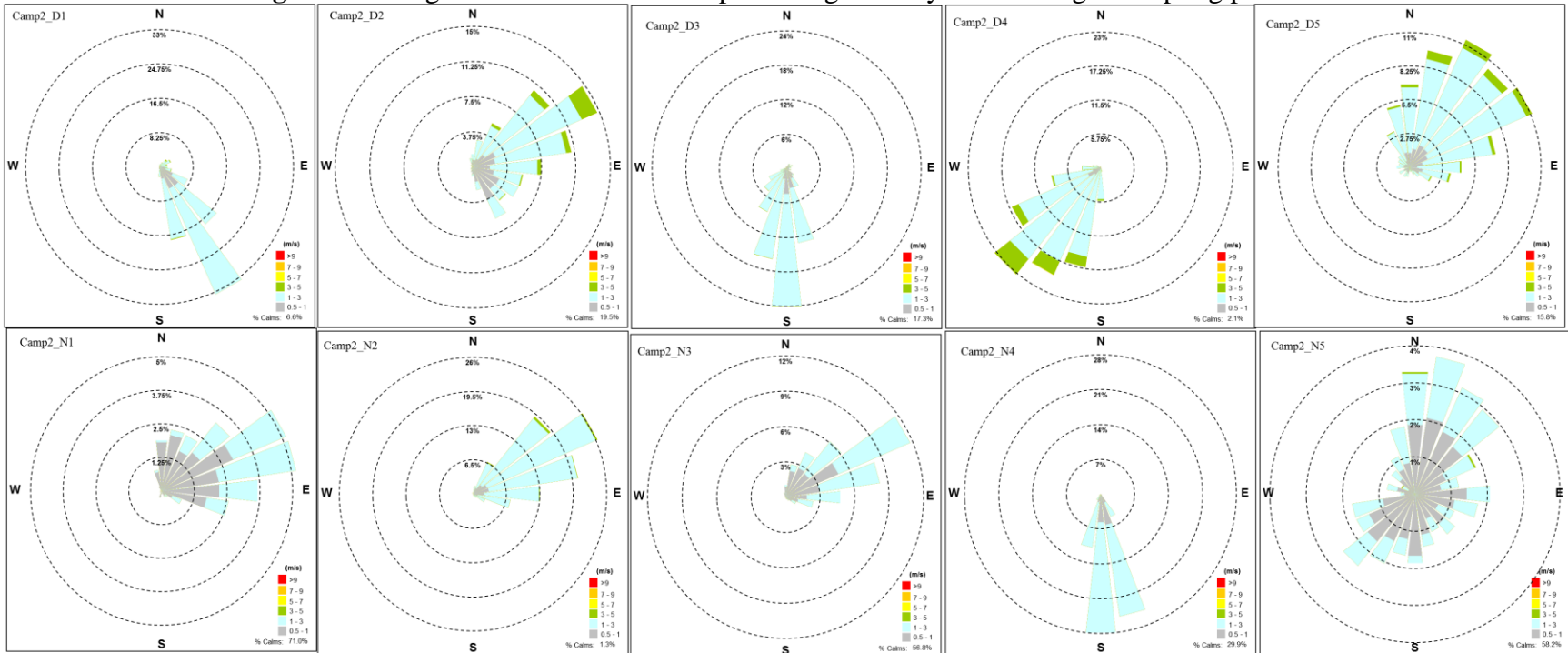
Values reported as average values of meteorological conditions of five day (night) filed sampling period, followed by standard deviations (in parentheses). <sup>a</sup>percentage of the time period under the calm condition (wind speed < 0.3 m/s) during an experimental sampling period.



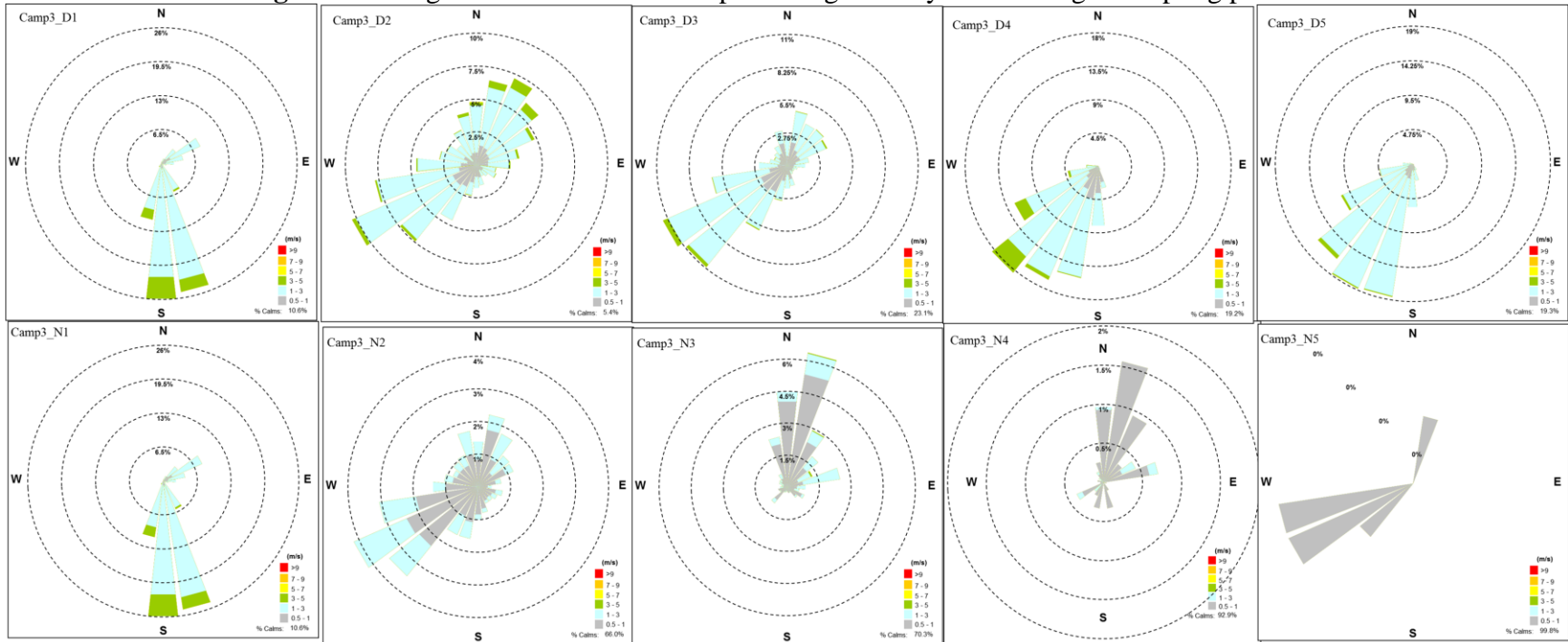
**Figure 1.** Background wind rose at Camp 1 during five day and five night sampling periods.



**Figure 2.** Background wind rose at Camp 2 during five day and five night sampling periods.



**Figure 3.** Background wind rose at Camp 3 during five day and five night sampling periods.



**Table 2.** Observed and predicted PM<sub>2.5</sub> and NH<sub>3</sub> concentrations from Campaign 1

<b>Campaign 1, PM<sub>2.5</sub> Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1.27	0.00	2.20	2.76	2.38	0.69	1.18	1.65	2.32	1.51
T1-2	1.13	0.00	1.75	1.00	0.00	0.00	0.70	2.47	1.06	0.49
T1-3	0.00	0.00	0.94	0.00	1.15	1.81	0.00	0.10	0.00	0.00
T2-1	0.04	0.00	2.06	3.49	1.95	0.00	1.81	0.12	2.40	2.45
T2-2	1.17	1.49	2.33	3.39	3.84	0.00	1.59	2.11	2.25	2.65
T2-3	0.62	1.46	1.99	2.08	2.61	0.00	0.00	1.71	1.84	2.02
T2-4	0.00	0.00	0.53	2.05	1.72	0.00	0.00	1.12	1.49	0.00
T2-5	0.00	0.00	0.00	0.00	0.92	0.00	0.00	0.00	0.00	0.01
T3-1	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T3-2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T3-3	0.00		0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T3-4	0.00		0.59	0.00	0.00	0.00	0.00	0.08	0.07	0.00
T3-5	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.06
T3-6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.32	0.12

<b>Campaign 1, PM<sub>2.5</sub> Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1.13	0.00	1.74	1.00	0.00	0.00	0.70	2.44	1.05	0.49
T1-2	1.13	0.00	1.75	1.00	0.00	0.00	0.70	2.47	1.06	0.49
T1-3	0.92	0.00	1.44	0.82	0.00	0.00	0.57	1.68	0.75	0.37
T2-1	0.70	0.00	1.07	0.62	0.00	0.00	0.43	1.54	0.74	0.30
T2-2	0.72	0.00	1.09	0.63	0.00	0.00	0.44	1.74	0.82	0.32
T2-3	0.68	0.00	1.03	0.59	0.00	0.00	0.42	1.64	0.77	0.31
T2-4	0.53	0.00	0.82	0.47	0.00	0.00	0.33	1.07	0.53	0.22
T2-5	0.19	0.00	0.32	0.18	0.00	0.00	0.12	0.17	0.10	0.05
T3-1	0.31	0.00	0.47	0.27	0.00	0.00	0.19	0.80	0.42	0.14
T3-2	0.31	0.00	0.46	0.26	0.00	0.00	0.19	0.78	0.41	0.14
T3-3	0.30	0.00	0.44	0.26	0.00	0.00	0.18	0.76	0.40	0.14
T3-4	0.27	0.00	0.41	0.24	0.00	0.00	0.17	0.70	0.37	0.12
T3-5	0.22	0.00	0.33	0.19	0.00	0.00	0.13	0.52	0.28	0.10
T3-6	0.15	0.00	0.23	0.13	0.00	0.00	0.09	0.30	0.17	0.06

<b>Campaign 1, NH<sub>3</sub> Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	3199	1806	3012	2678	3507	2448	2402	2685	3605	2530
T1-2	3033	1717	2779	2542	3248	2369	2427	2540	3107	2034
T1-3	1598	1025	1093	1081	1450	905	1093	851	1143	902
T2-1	2405	1422	2663	2492	3166	2475	2690	2858	3151	2471
T2-2	2760	1621	2743	2709	3148	2465	2800	2772	3466	2518
T2-3	2149	1484	1998	2187	2974	2209	2306	2471	2886	2212
T2-4	2616	1244	1127	1558	2027	1412	1806	1379	1766	1435
T2-5	1149	838	368	883	1339	889	1122	719	1037	821
T3-1	29	9	590	148	105	71	75	272	102	76
T3-2	45	9	749	218	150	128	120	383	169	123
T3-3	49	12	815	247	172	240	193	293	271	209
T3-4	56	13	858	293	192	382	316	294	464	391
T3-5	72	15	800	374	236	836	766	459	1092	926
T3-6	75	20	591	355	218	839	834	519	1238	1043

<b>Campaign 1, NH<sub>3</sub> Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	3017	1710	2768	2532	3231	2350	2415	2510	3074	2016
T1-2	3033	1717	2779	2542	3248	2369	2427	2540	3107	2034
T1-3	2464	1423	2288	2097	2645	1811	1974	1735	2204	1526
T2-1	1871	1063	1705	1567	2034	1456	1501	1591	2170	1246
T2-2	1922	1077	1735	1592	2086	1554	1542	1793	2404	1344
T2-3	1830	1023	1649	1513	1986	1482	1468	1693	2279	1281
T2-4	1437	818	1310	1203	1563	1096	1155	1106	1553	928
T2-5	530	331	516	475	582	315	431	192	316	248
T3-1	850	470	755	691	933	710	686	830	1251	614
T3-2	833	461	741	678	914	695	673	816	1228	601
T3-3	805	446	717	656	884	671	651	791	1187	581
T3-4	746	415	666	609	819	619	604	730	1092	535
T3-5	594	335	535	489	653	481	482	543	821	414
T3-6	419	242	384	351	462	322	343	319	501	273

**Table 3.** Observed and predicted PM<sub>2.5</sub> and NH<sub>3</sub> concentrations from Campaign 2

<b>Campaign 2, PM<sub>2.5</sub> Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1.35	1.03	0.96	0.84	1.31	0.53	0.00	0.00	0.21	1.06
T1-2	1.83	1.51	0.46	0.60	0.81	0.53	0.18	0.22	0.34	0.47
T1-3	1.25	1.07	0.50	0.00	0.48		0.05	0.08	0.47	0.00
T2-1	0.07	0.00	0.30	0.85	1.02	0.54	0.00	0.38	0.46	0.67
T2-2	0.01	0.06	0.46	0.85	1.63	0.88	0.14	0.24	0.70	0.71
T2-3	0.01	0.00	0.00	0.00	0.85	0.56	0.24	0.51	0.65	0.36
T2-4	0.00	0.04	0.86	0.54	0.51	0.00	0.03	0.26	0.49	0.00
T2-5	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.15	0.00
T3-1	0.00		0.00	0.00	0.00	0.00		0.02		0.00
T3-2			0.00	0.00	0.00	0.00		0.00	0.00	0.00
T3-3				0.00	0.00	0.00		0.00	0.00	0.00
T3-4					0.05	0.00		0.00	0.00	0.00
T3-5	2.65		0.00		0.00	0.00		0.00	0.00	0.00
T3-6			0.04		0.00	0.00		0.00	0.04	0.00

<b>Campaign 2, PM<sub>2.5</sub> Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1.81	1.51	0.45	0.60	0.80	0.52	0.18	0.22	0.33	0.46
T1-2	1.83	1.51	0.46	0.60	0.81	0.53	0.18	0.22	0.34	0.47
T1-3	1.46	1.21	0.24	0.50	0.65	0.36	0.14	0.15	0.23	0.33
T2-1	1.06	1.07	0.23	0.35	0.44	0.33	0.10	0.23	0.19	0.25
T2-2	1.10	1.13	0.30	0.36	1.18	0.37	0.11	0.26	0.21	0.28
T2-3	1.04	1.05	0.26	0.34	0.43	0.35	0.10	0.25	0.20	0.26
T2-4	0.80	0.79	0.14	0.27	0.34	0.23	0.08	0.16	0.13	0.17
T2-5	0.28	0.30	0.03	0.11	0.12	0.04	0.03	0.03	0.02	0.03
T3-1	0.46	0.51	0.10	0.15	0.18	0.15	0.04	0.18	0.09	0.10
T3-2	0.45	0.54	0.10	0.15	0.17	0.15	0.04	0.17	0.09	0.10
T3-3	0.43	0.63	0.11	0.14	0.17	0.14	0.04	0.17	0.08	0.10
T3-4	0.40	0.67	0.11	0.13	0.16	0.13	0.04	0.16	0.08	0.09
T3-5	0.31	0.37	0.07	0.11	0.12	0.10	0.03	0.11	0.06	0.07
T3-6	0.22	0.25	0.03	0.08	0.09	0.06	0.02	0.07	0.03	0.04

<b>Campaign 2, NH<sub>3</sub> Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	2983	4381	5171	4682	6842	1955	3403	1775	4447	4608
T1-2	2956	2757	3918	4505	5383	950	2164	1490	3680	4212
T1-3	2597	2323	1953	2158	1977	532	2069	1444	2529	1232
T2-1	684	1113	3858	4534	4762	3531	1612	2467	3515	3128
T2-2	3080	622	1400	986	2184	4023	3753	4299	3417	4373
T2-3	531	839	3680	4041	2593	2095	1098	1635	3385	2141
T2-4	316	663	2622	2288	1356	761	576	1232	2458	1193
T2-5	117	311	1076	418	536	416	154	701	1229	551
T3-1	15	6	21	24	511	158	11	68	20	227
T3-2	14	8	25	24	322	251	5	89	26	323
T3-3	7	8	25	25	384	315	6	109	34	387
T3-4	8	8	27	22	340	398	6	124	57	444
T3-5	8	14	44	20	368	392	6	245	80	646
T3-6	6	21	45	13	320	261	7	327	60	555

<b>Campaign 2, NH<sub>3</sub> Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	2939	2757	3815	4489	5357	939	2152	1475	3638	4166
T1-2	2956	2757	3918	4505	5383	950	2164	1490	3680	4212
T1-3	2368	2225	2102	3724	4368	662	1756	1066	2541	2946
T2-1	1731	1974	1995	2656	2974	607	1315	1588	2081	2222
T2-2	1795	2077	2600	2693	3052	679	1359	1776	2337	2476
T2-3	1709	1942	2261	2557	2901	644	1299	1682	2211	2344
T2-4	1324	1478	1167	2037	2272	435	1033	1133	1462	1577
T2-5	480	607	277	811	857	108	448	265	256	310
T3-1	769	983	834	1116	1211	301	647	1222	958	946
T3-2	754	1036	905	1095	1188	296	637	1204	941	929
T3-3	730	1181	983	1060	1150	289	621	1170	911	900
T3-4	677	1264	989	984	1067	269	584	1085	839	829
T3-5	542	720	602	791	854	211	490	824	626	625
T3-6	385	503	305	567	607	141	381	511	372	382

**Table 4.** Observed and predicted PM<sub>2.5</sub> and NH<sub>3</sub> concentrations from Campaign 3

<b>Campaign 3, PM<sub>2.5</sub> Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	1.09	0.56	1.33	0.74	0.81	0.00	0.00	0.52	0.00	0.13
T1-2	0.00	0.00	0.66	0.52	0.56	0.29	0.00	0.00	0.00	0.04
T1-3	0.07	0.06	0.02	0.17	0.00	0.00	0.00	0.00	0.00	0.00
T1-4	0.03	0.00	0.00	0.37	0.32	0.00	0.00	0.00	0.00	0.00
T1-6	0.00	0.00	0.00	0.13	0.11	0.00	0.00	0.01	0.00	0.00
T2-1	0.00	0.97	0.75	1.70	0.00	0.16	0.00	0.38	0.35	
T2-2	0.00	0.97	1.34	0.71	1.00	0.22	0.29	0.35	0.48	0.23
T2-3	0.00	0.69	0.67	1.09	1.13	0.01	0.00	0.30	0.43	0.18
T2-4	0.00	0.08	0.33	1.04	1.06	0.00	0.02	0.02	0.04	0.04
T2-5	0.00	0.00	0.00	0.85	0.69	0.00	0.00	0.00	0.00	0.00
T3-1		0.00	0.00			0.00	0.00	0.00	0.00	0.00
T3-2		0.00	0.01		0.00	0.00	0.01	0.00	0.00	0.01
T3-3		0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.02
T3-4		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01

<b>Campaign 3, PM<sub>2.5</sub> Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	0.00	0.00	0.66	0.51	0.56	0.29	0.00	0.00	0.00	0.04
T1-2	0.00	0.00	0.66	0.52	0.56	0.29	0.00	0.00	0.00	0.04
T1-3	0.00	0.00	0.55	0.28	0.45	0.22	0.00	0.00	0.00	0.03
T1-4	0.00	0.00	0.31	0.12	0.22	0.08	0.00	0.00	0.00	0.01
T1-6	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00
T2-1	0.00	0.00	0.42	0.27	0.34	0.25	0.00	0.00	0.00	0.03
T2-2	0.00	0.00	0.43	0.35	0.35	0.27	0.00	0.00	0.00	0.03
T2-3	0.00	0.00	0.40	0.30	0.33	0.26	0.00	0.00	0.00	0.03
T2-4	0.00	0.00	0.32	0.16	0.26	0.18	0.00	0.00	0.00	0.02
T2-5	0.00	0.00	0.14	0.05	0.09	0.05	0.00	0.00	0.00	0.01
T3-1	0.00	0.00	0.17	0.12	0.14	0.16	0.00	0.00	0.00	0.02
T3-2	0.00	0.00	0.16	0.14	0.13	0.15	0.00	0.00	0.00	0.02
T3-3	0.00	0.00	0.13	0.08	0.10	0.11	0.00	0.00	0.00	0.01
T3-4	0.00	0.00	0.09	0.04	0.07	0.06	0.00	0.00	0.00	0.01



<b>Campaign 3, NH<sub>3</sub> Observed Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	3837	4142	4107	4770	4746	3298	5570	2568	2720	2865
T1-2	3875	4594	3470	3880	3773	3020	5152	2231	2516	2387
T1-3	798	232	300	2	2051	2	301	213	2111	190
T1-4	238	119	215	2	2376	331	178	193	2122	202
T1-5	246	82	169	2	1443	307	154	150	1549	197
T2-1	354	2846	3257	1969	2356	1854	3991	2051	1875	2125
T2-2/R	322	2214	3317	2236	2836	2175	3810	1861	1790	2126
T2-3	154	1127	1498	917	4276	609	1416	719	1351	1528
T2-4	72	413	770	3644	3349	726	704	314	674	896
T3-1	16	336	298	19	41	128	659	387	337	520
T3-2	10	413	350	26	53	196	704	414	391	722
T3-3	11	437	418	61	83	N/A	782	478	509	930
T3-4	9	292	294	63	89	105	642	409	187	957

<b>Campaign 3, NH<sub>3</sub> Predicted Concentrations (ug/m<sup>3</sup>)</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	3900	4548	3499	3770	3764	2995	5186	2214	2495	2367
T1-2	3875	4594	3470	3880	3773	3020	5152	2231	2516	2387
T1-3	2001	1152	1640	895	1495	922	2628	717	770	703
T1-4	473	46	398	110	212	105	571	48	60	44
T1-5	153	6	116	41	73	75	139	15	31	20
T2-1	3424	3507	2233	1976	2272	2571	4546	1990	1856	1746
T2-2/R	3411	3908	2258	2625	2348	2768	4527	2109	1982	1870
T2-3	2641	2460	1706	1199	1744	1924	3491	1501	1396	1308
T2-4	1259	498	768	389	649	539	1630	445	401	359
T3-1	1742	2174	926	917	979	1658	2280	1176	1011	943
T3-2	1585	1961	841	1049	878	1567	2069	1046	900	838
T3-3	1311	1449	688	609	701	1130	1699	812	699	648
T3-4	989	830	507	332	496	725	1265	543	467	428

## Appendices C: Chapter 5 supplementary information

**Table 1.** Meteorological conditions of 10 experiments at Farm 1

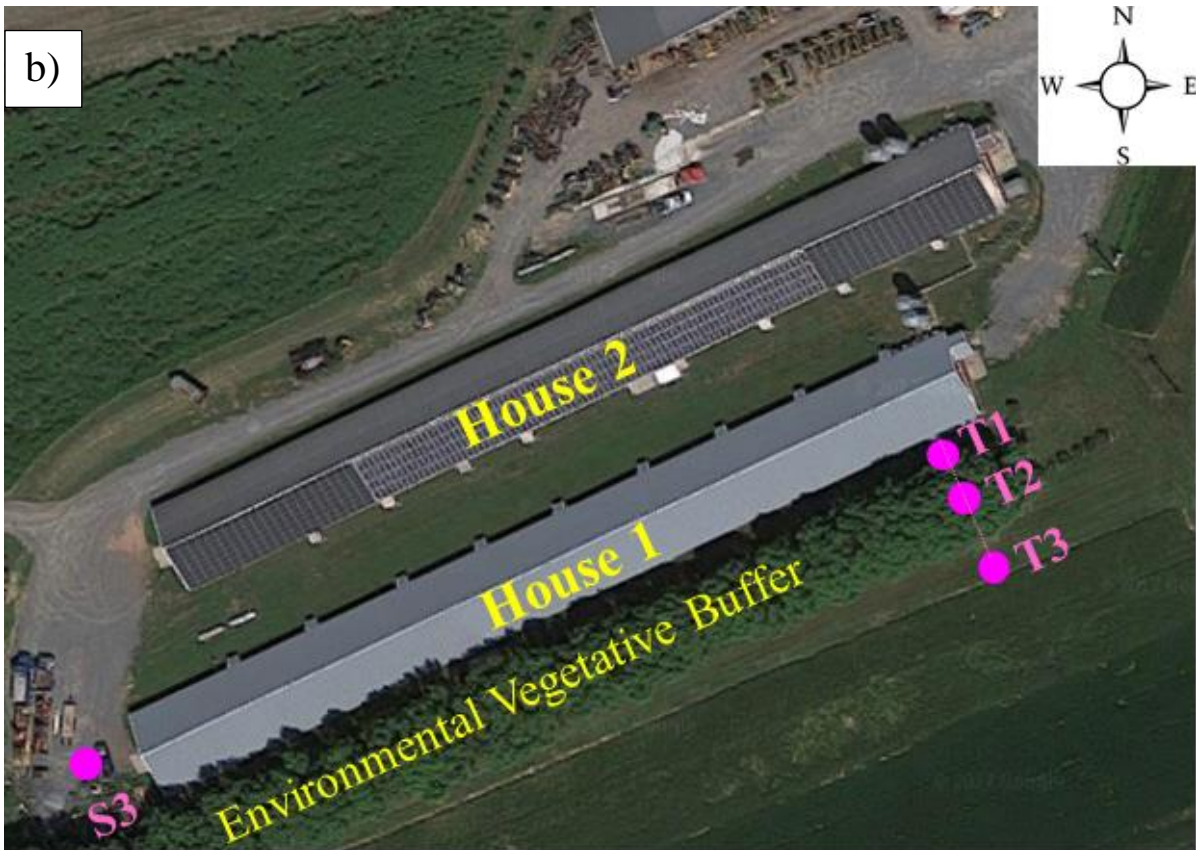
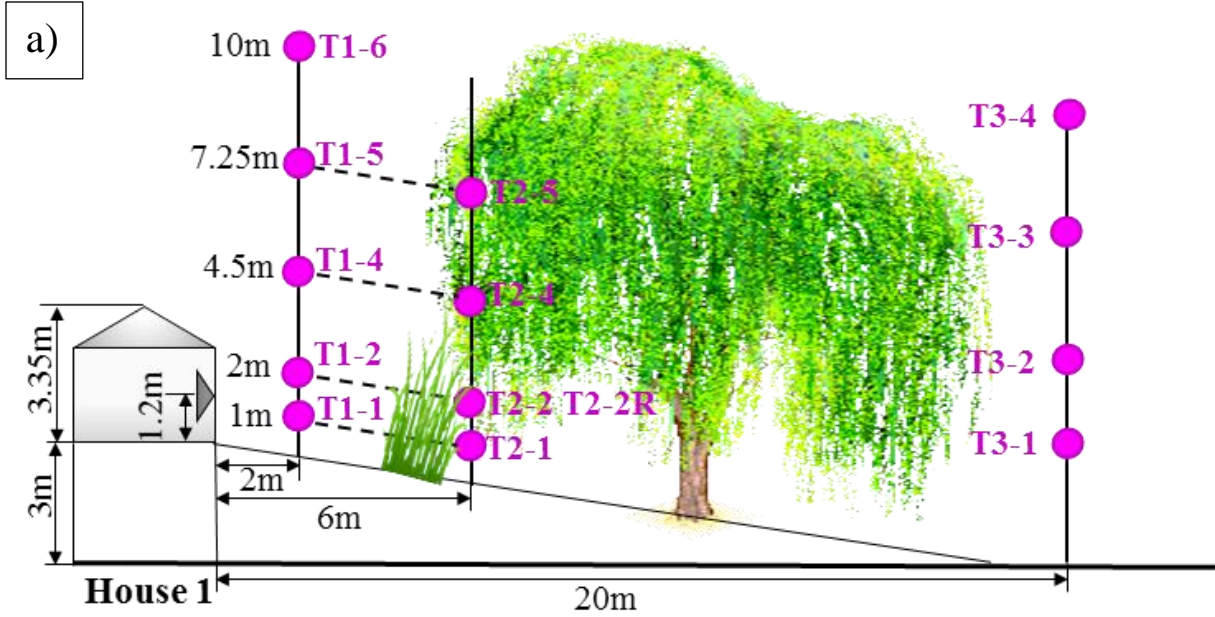
Experiment	T (°C)	Relative Humidity	Pressure (atm)	Wind Speed (m/s)	Wind Direction
Farm 1-D1	26.9 (0.4)	50.6% (1.1%)	0.882 (0.007)	0.6 (0.3) 69% <0.5	W, SW
Farm 1-D2	26.4 (0.9)	51.7% (2.0%)	0.882 (0.010)	0.6 (0.4) 77% <0.5	W, SW, N
Farm 1-D3	26.7 (0.7)	43.8% (1.9%)	0.882 (0.007)	0.8 (0.4) 38% <0.5	W, NW, N
Farm 1-D4	26.0 (0.6)	46.5% (1.8%)	0.896 (0.020)	0.4 (0.3) 77% <0.5	W, NW
Farm 1-D5	29.8 (0.3)	54.7% (1.0%)	0.889 (0.010)	2.1 (0.3) 0% <0.5	SW
Farm 1-N1	24.3 (0.4)	63.7% (1.8%)	0.939 (0.007)	100% <0.5	NW, N
Farm 1-N2	23.0 (0.6)	67.7% (1.8%)	0.929 (0.003)	100% <0.5	NW, N
Farm 1-N3	20.6 (1.1)	68.8% (5.1%)	0.939 (0.003)	100% <0.5	N, NW
Farm 1-N4	19.1 (2.0)	62.8% (8.2%)	0.956 (0.007)	100% <0.5	NW
Farm 1-N5	23.2 (0.7)	69.6% (2.8%)	0.942 (0.003)	100% <0.5	N, NW

\*Average (Standard Deviation)

**Table 2.** Meteorological conditions of 10 experiments at Farm 2

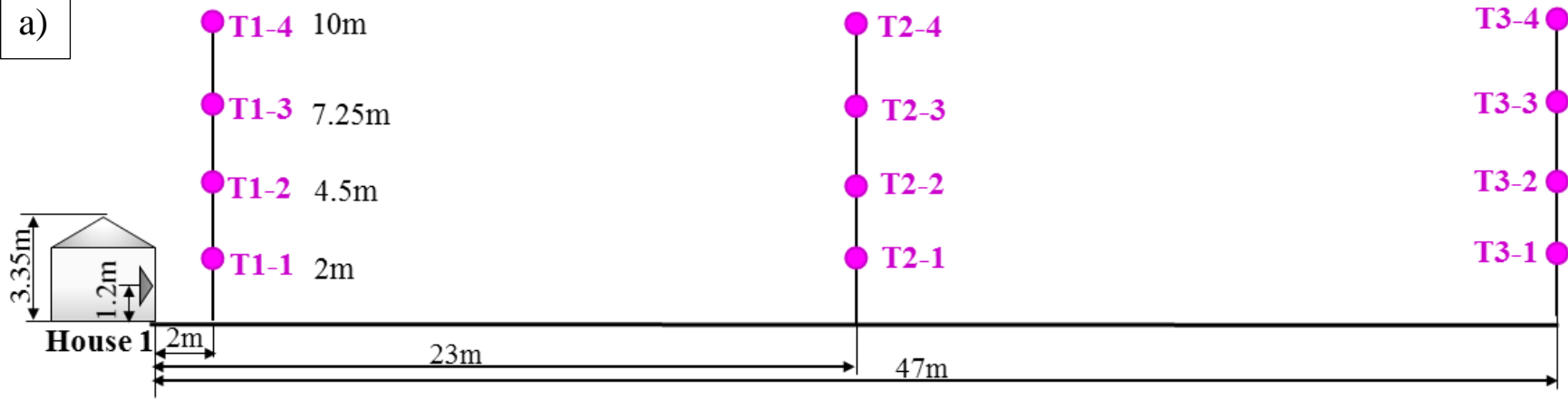
Experiment	T (°C)	Relative Humidity	Pressure (atm)	Wind Speed (m/s)	Wind Direction
Farm 2-D1	25.7 (1.5)	79.3% (5.9%)	-	0.4 (0.3) 69% <0.5	SW, W, N
Farm 2-D2	21.1 (0.4)	94.5% (1.2%)	0.963 (0.007)	0.6 (0.5) 54% <0.5	N
Farm 2-D3	13.5 (1.2)	85.1% (4.4%)	0.996 (0.017)	1.7 (0.7) 0% <0.5	NW
Farm 2-D4	19.0 (0.7)	57.6% (3.2%)	0.976 (0.007)	2.8 (0.3) 0% <0.5	NW
Farm 2-D5	21.5 (0.6)	47.8% (4.1%)	0.953 (0.003)	3.2 (0.4) 0% <0.5	NW
Farm 2-N1	22.0 (0.2)	84.8% (1.1%)	0.939 (0.007)	0.4 (0.3) 69% <0.5	SW, W
Farm 2-N2	20.8 (1.0)	91.7% (1.2%)	0.989 (0.003)	1.6 (0.6) 0% <0.5	E
Farm 2-N3	23.6 (0.9)	81.4% (5.6%)	0.949 (0.003)	0.3 (0.4) 92% <0.5	SW, NW
Farm 2-N4	16.0 (1.1)	62.9% (3.7%)	1.010 (0.007)	1.2 (0.3) 0% <0.5	N
Farm 2-N5	18.6 (0.9)	57.5% (4.6%)	0.942 (0.003)	0.4 (0.4) 69% <0.5	W

\*Average (Standard Deviation)



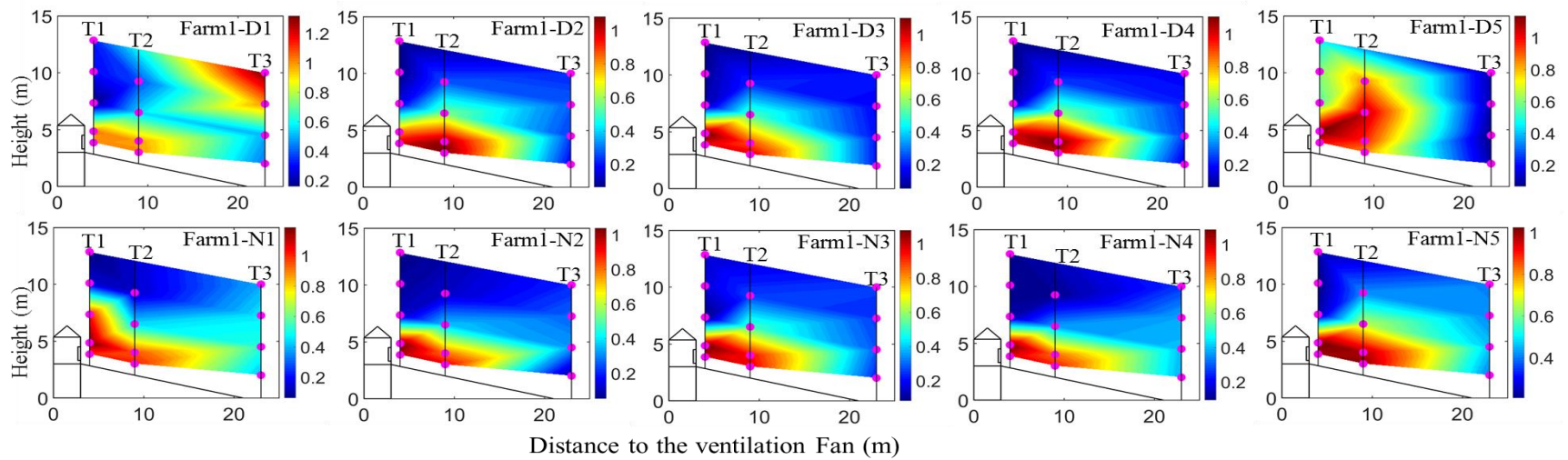
**Figure 1.** Farm 1 experimental set up a) sketch, and b) map

a)

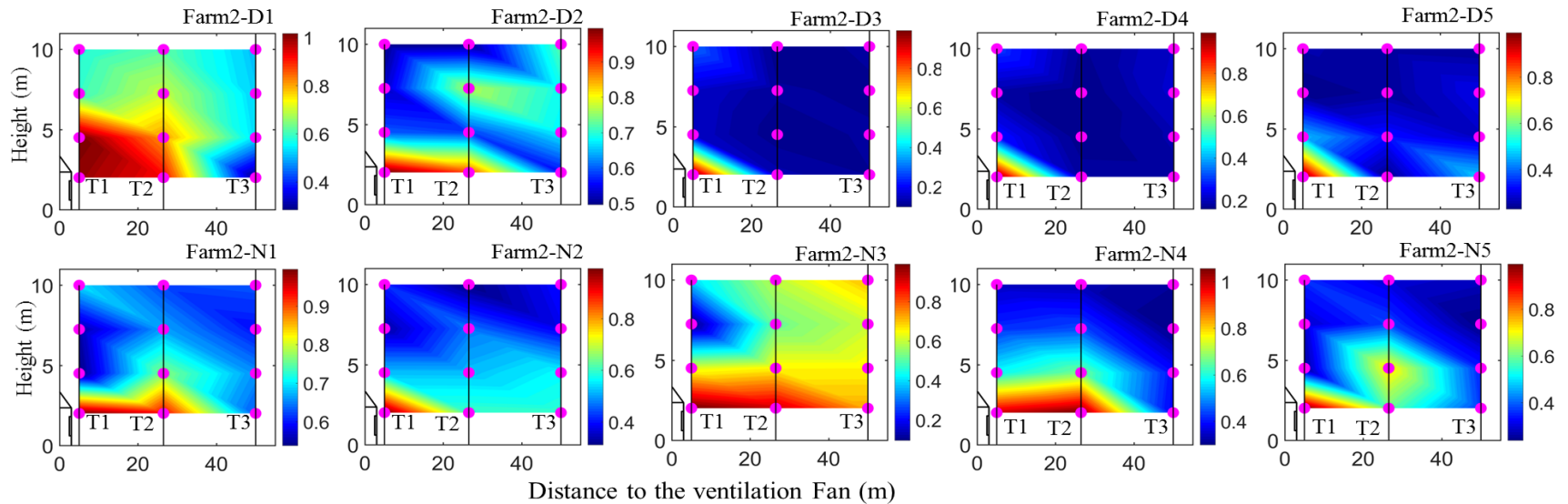




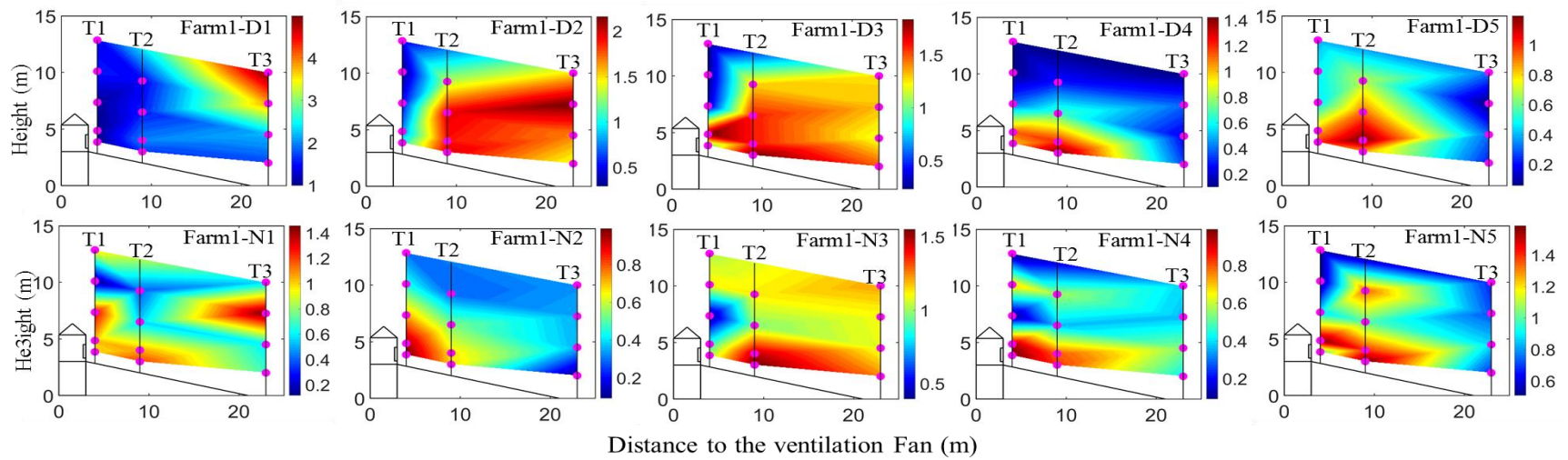
**Figure 2.** Farm 2 experimental set up a) sketch, and b) map



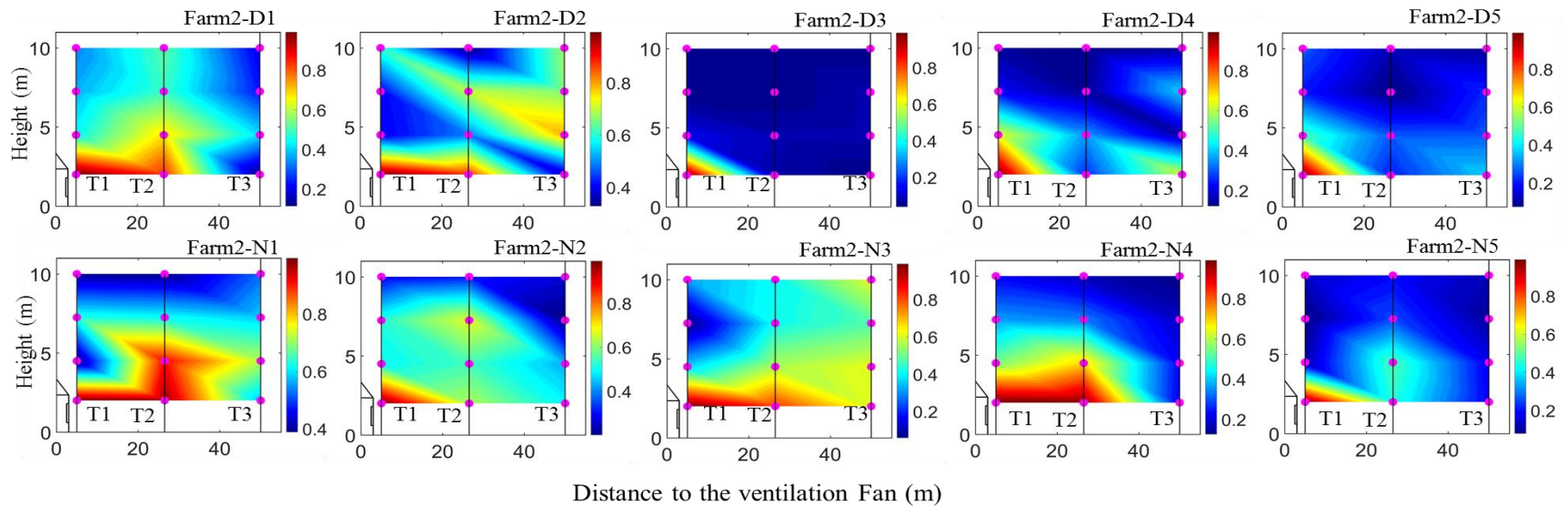
**Figure 3.** Methanol emission patterns from individual experiments at Farm 1



**Figure 4.** Methanol emission gradients from individual experiments at Farm 2

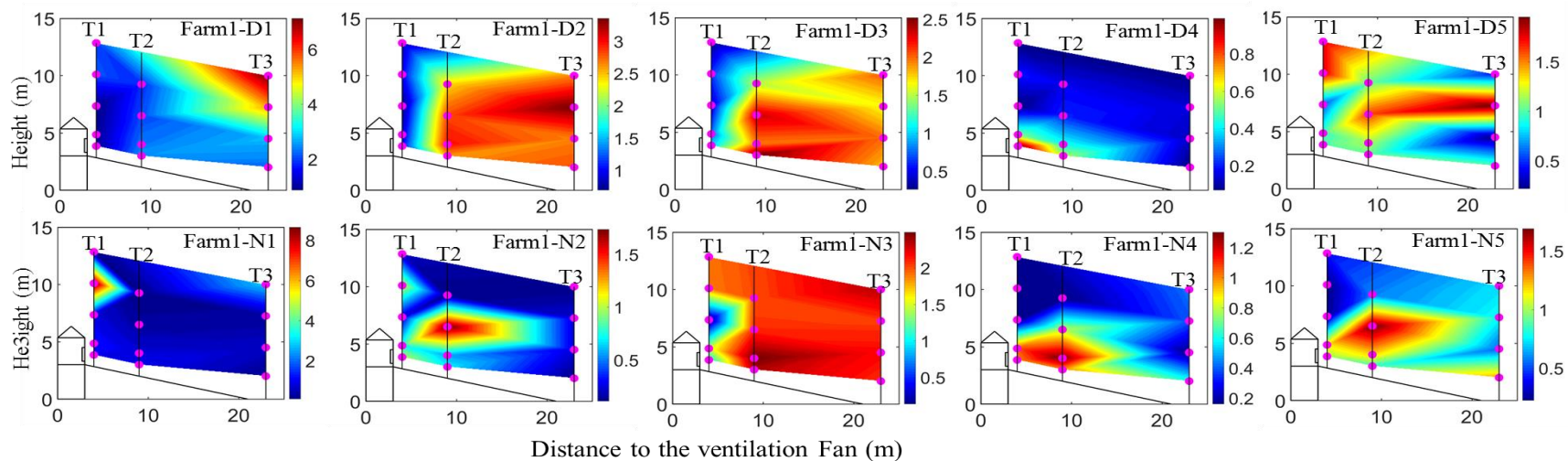


**Figure 5.** Ethanol emission patterns from individual experiments at Farm 1

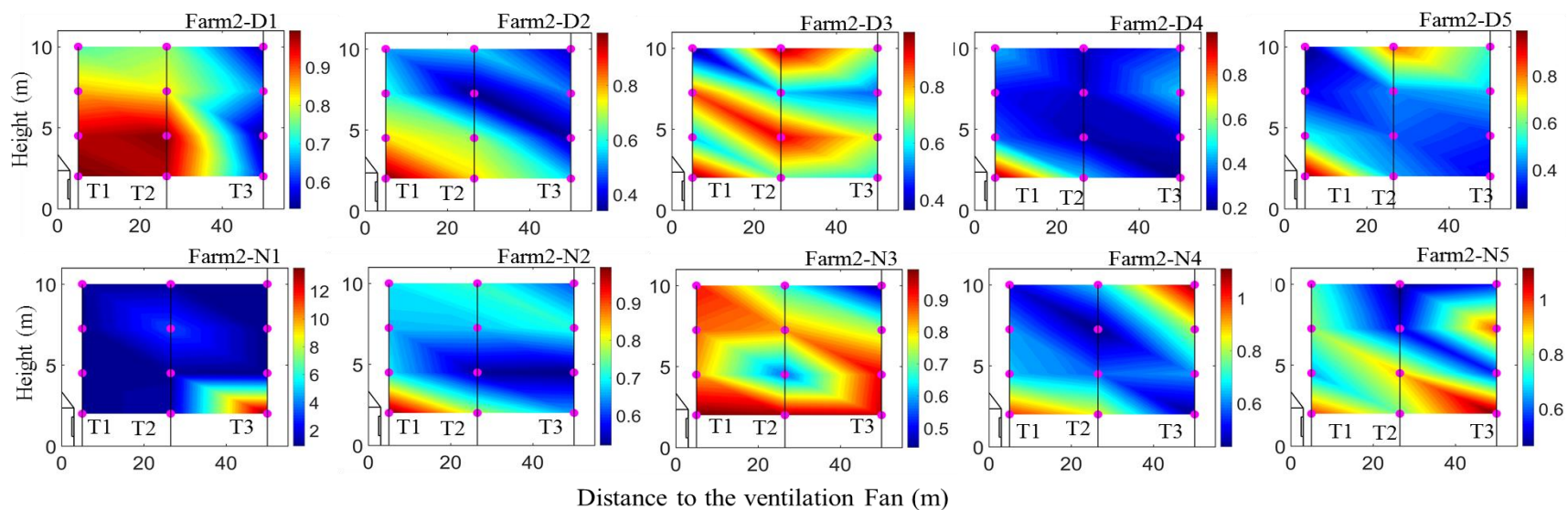


**Figure 6.** Ethanol emission gradients from individual experiments at Farm 2

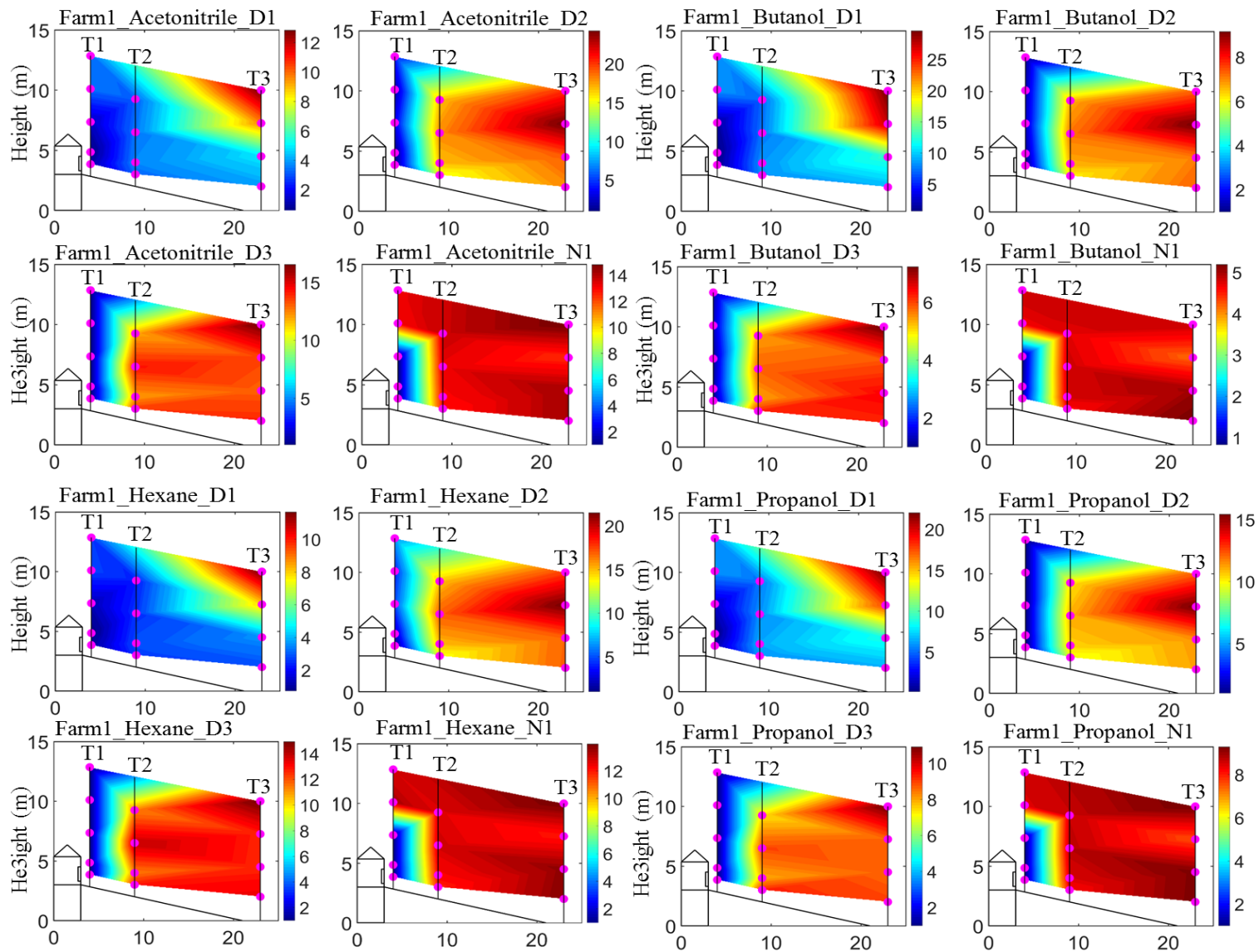


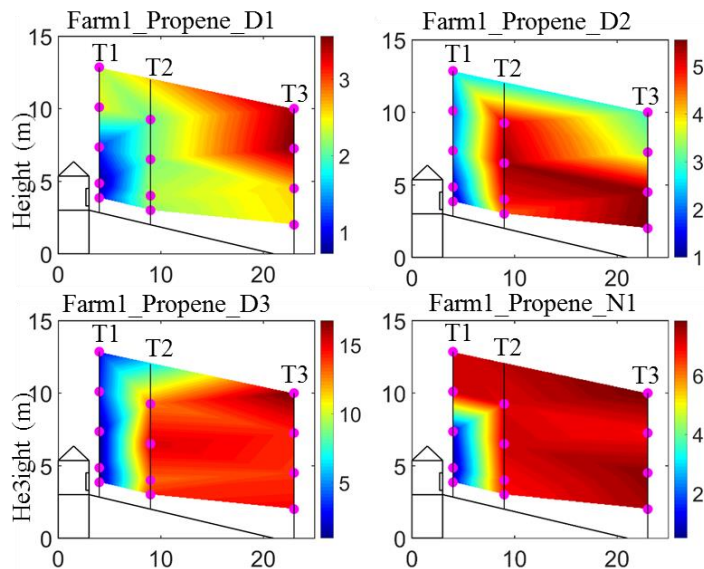


**Figure 7.** Acetone gradients patterns from individual experiments at Farm 1



**Figure 8.** Acetone emission gradients from individual experiments at Farm 2





**Figure 9.** Non-source VOC emission gradients from individual experiments at Farm 1

**Table 2.** VOC concentrations from each experiment at Farm 1 and Farm 2.

Sample	Methanol Concentration ( $\mu\text{g}/\text{m}^3$ ) at Farm 1									
	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	197	154	185	147	174	212	213	166	159	195
T1-2	226	128	206	150	200	254	223	180	174	201
T1-4	35	25	18	17	97	218	23	14	20	47
T1-5	67	10	14	10	105	33	18	28	15	41
T1-6	74	10	10	9	80	14	12	25	17	46
T2-1	220	168	185	153	150	215	197	161	149	197
T2-2	225	166	167	152	167	199	171	156	135	194
T2-2R	209	159	165	176	169	205	171	159	137	193
T2-4	121	88	98	88	187	96	79	87	59	130
T2-5	84	42	41	37	148	30	26	44	18	82
T3-1	96	28	37	23	18	86	13	39	61	79
T3-2	110	38	37	36	12	112	68	48	63	91
T3-3	220	43	33	33	20	97	58	43	61	81
T3-4	292	35	37	26	19	83	45	44	42	80
Background	2	80	21	6	10	4	2	10	11	14

<b>Ethanol Concentration (ug/m<sup>3</sup>) at Farm 1</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	41	19	21	20	34	17	22	25	22	27
T1-2	43	15	39	23	29	18	21	21	21	43
T1-4	44	10	7	8	15	22	16	10	2	24
T1-5	65	6	5	2	16	2	10	28	15	14
T1-6	58	9	5	2	13	17	7	25	2	14
T2-1	70	38	39	29	30	21	15	38	18	43
T2-2	80	32	29	21	36	19	13	35	17	41
T2-2R	82	41	38	27	46	18	16	38	18	35
T2-4	65	38	33	14	32	10	12	24	8	27
T2-5	59	26	27	6	23	7	6	28	12	36
T3-1	71	28	31	7	8	12	2	31	9	18
T3-2	90	33	25	5	11	10	8	27	12	24
T3-3	157	42	28	8	2	25	8	27	8	19
T3-4	205	29	27	2	11	10	7	30	9	18
Background	12	84	28	11	2	2	9	13	13	15

<b>Acetone Concentration (ug/m<sup>3</sup>) at Farm 1</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	49	16	21	36	27	23	23	18	15	21
T1-2	48	15	16	19	26	29	17	26	16	24
T1-3	43	11	9	3	15	20	6	3	3	5
T1-4	104	16	14	7	47	201	23	34	3	5
T1-5	99	13	6	3	47	3	5	35	3	9
T2-1	124	43	53	20	28	23	16	43	15	18
T2-2	118	47	36	13	26	17	14	47	15	19
T2-2R	113	51	46	18	35	20	12	43	26	30
T2-3	102	47	49	8	43	8	39	38	12	36
T2-4	93	40	32	6	28	3	3	36	3	12
T3-1	112	46	38	3	27	6	3	38	10	26
T3-2	137	44	42	5	6	15	6	39	3	11
T3-3	260	55	35	5	52	8	5	37	6	16
T3-4	352	44	42	3	13	66	3	43	7	15
background	3	88	40	8	3	3	3	13	3	3

<b>Butanol Concentration (ug/m<sup>3</sup>) at Farm 1</b>				
Sample	Day 1	Day 2	Day 3	Night 1
T1-1	19	8	7	9
T1-2	14	9	8	8
T1-3	31	11	8	7
T1-4	160	10	9	42
T1-5	155	9	9	43
T2-1	156	47	44	41
T2-2	168	49	34	45
T2-2R	150	52	43	42
T2-3	141	54	41	43
T2-4	134	50	39	43
T3-1	176	55	44	47
T3-2	242	53	45	45
T3-3	516	70	42	37
T3-4	559	55	52	44
background	3	120	56	11

<b>Acetonitrile Concentration (ug/m<sup>3</sup>) at Farm 1</b>				
Sample	Day 1	Day 2	Day 3	Night 1
T1-1	18	2	2	2
T1-2	11	2	2	2
T1-3	24	5	2	2
T1-4	62	3	2	20
T1-5	61	7	2	20
T2-1	61	23	21	19
T2-2	70	25	16	20
T2-2R	63	26	20	19
T2-3	63	27	21	20
T2-4	58	25	18	21
T3-1	72	27	21	21
T3-2	87	29	20	21
T3-3	174	37	20	19
T3-4	233	30	25	22
background	BLD	66	25	7

<b>Hexane Concentration (ug/m<sup>3</sup>) at Farm 1</b>				
Sample	Day 1	Day 2	Day 3	Night 1
T1-1	47	4	4	4
T1-2	34	8	4	4
T1-3	60	17	4	4
T1-4	132	15	4	47
T1-5	126	23	4	45
T2-1	125	47	45	42
T2-2	140	50	35	44
T2-2R	129	56	46	43
T2-3	122	60	49	45
T2-4	111	53	40	44
T3-1	134	59	47	48
T3-2	167	59	44	48
T3-3	374	76	45	42
T3-4	549	62	53	49
background	BLD	125	57	22

<b>Propanol Concentration (ug/m<sup>3</sup>) at Farm 1</b>				
Sample	Day 1	Day 2	Day 3	Night 1
T1-1	16	3	3	3
T1-2	3	3	3	3
T1-3	25	3	3	3
T1-4	97	3	3	26
T1-5	96	3	3	26
T2-1	96	29	28	25
T2-2	108	31	21	26
T2-2R	98	33	27	25
T2-3	93	33	27	26
T2-4	84	31	22	26
T3-1	104	34	27	28
T3-2	139	34	26	28
T3-3	281	47	26	23
T3-4	350	37	33	28
background	BLD	88	34	2

**Propene Concentration (ug/m<sup>3</sup>) at Farm 1**

Sample	Day 1	Day 2	Day 3	Night 1
T1-1	14	5	2	3
T1-2	10	7	2	2
T1-3	17	12	2	3
T1-4	35	10	5	22
T1-5	33	14	4	22
T2-1	32	24	21	21
T2-2	35	26	18	22
T2-2R	31	28	22	21
T2-3	30	29	23	22
T2-4	30	28	19	22
T3-1	37	30	22	23
T3-2	37	29	21	24
T3-3	51	18	21	21
T3-4	50	16	25	24
background	BLD	66	25	12

**Methanol Concentration (ug/m<sup>3</sup>) at Farm 2**

Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	136	109	138	99	96	N/A	137	118	69	98
T1-2	139	66	22	27	45	57	72	74	41	25
T1-3	81	58	22	19	22	59	46	11	30	29
T1-4	78	54	41	31	25	73	57	47	24	35
T2-1	127	115	17	19	24	98	83	104	83	68
T2-2R	124	82	22	18	21	101	82	116	65	49
T2-2	110	64	15	16	32	81	72	78	46	71
T2-3	95	84	17	16	24	70	64	62	31	37
T2-4	84	55	14	17	24	66	43	71	23	30
T3-1	39	62	16	18	46	67	82	86	27	36
T3-2	73	74	17	20	27	69	77	78	28	35
T3-3	71	76	15	22	29	63	52	71	21	23
T3-4	69	80	17	22	24	67	55	84	22	28
background	87	53	N/A	21	27	51	86	58	26	27

<b>Acetone Concentration (ug/m<sup>3</sup>) at Farm 2</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	35	41	41	24	36	626	34	69	40	38
T1-2	34	31	23	9	19	341	24	57	26	25
T1-3	981	25	36	7	11	26	23	181	25	31
T1-4	26	21	15	10	8	29	24	63	20	29
T2-1	34	30	15	8	11	36	27	62	39	33
T2-2R	34	33	40	14	21	35	26	73	28	26
T2-2	35	28	39	5	14	30	18	39	23	34
T2-3	29	14	23	6	15	90	23	58	17	20
T2-4	27	23	41	6	29	31	25	46	26	18
T3-1	1233	23	25	5	11	378	23	66	17	43
T3-2	19	14	30	6	13	24	18	65	25	21
T3-3	23	20	20	11	17	24	25	51	32	38
T3-4	19	15	29	8	20	25	21	30	44	21
background	24	19	N/A	6	23	23	32	27	33	25

<b>Ethanol Concentration (ug/m<sup>3</sup>) at Farm 2</b>										
Sample	Day 1	Day 2	Day 3	Day 4	Day 5	Night 1	Night 2	Night 3	Night 4	Night 5
T1-1	41	39	50	62	58	38	46	34	32	64
T1-2	18	16	7	40	28	15	23	13	18	8
T1-3	15	16	2	14	12	24	24	2	12	5
T1-4	14	24	2	9	15	15	13	11	7	9
T2-1	33	45	2	10	17	38	26	25	33	33
T2-2R	35	25	6	23	8	37	32	30	30	26
T2-2	28	19	4	22	15	35	25	19	22	32
T2-3	20	28	2	9	4	24	31	14	11	17
T2-4	21	13	2	8	7	15	15	14	5	12
T3-1	5	15	2	38	22	22	23	20	7	12
T3-2	17	31	4	10	16	28	20	21	7	11
T3-3	10	26	4	25	13	22	9	16	6	7
T3-4	8	27	2	9	6	20	12	21	4	8
background	13	11	N/A	31	6	12	26	18	14	7



## Glossary

**Animal feeding operations (AFOs):** confine animals for 45 days or more in a 12-month period in an area that does not produce grass or other vegetation during the normal growing season.

**Concentrated animal feeding operations (CAFOs):** subset of AFOs, with distinctions based primarily on size and pollution discharges. Only CAFOs are subject to regulation as point sources under the Clean Water Act.

**Poultry house:** The structure in which chickens are raised.

**Vegetative Environmental Buffer (VEB):** an air pollutant emission reduction practice for CAFOs, consist of trees, shrubs, grass, and potentially other plant materials.

**Field-observed concentration:** the concentration obtained from field sampling experiment and laboratory analysis.

**Model-predicted concentration:** the concentrations calculated by assuming strength equals to real value, and adjusted by observed background concentration.

**VEB collection efficiency:** equals to pollutant concentration reduction ratio. Using T1-2 concentration as the reference concentration.

$$collection\ eff. = \left(1 - \frac{Conc.i - Conc.ref}{Conc.ref}\right) \times 100\%$$

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