

ABSTRACT

WIEGAND, REBECCA DIANE. Fine Particulate Matter (PM_{2.5}) Pollution in Intensive Agricultural Region of North Carolina: Satellite Analysis and Integrate Ground-based Measurements. (Under the direction of Dr. Viney Aneja).

Intensive animal agriculture is an important part of North Carolina's economy. About ~ 10 million hogs, and about 1 billion chickens and turkeys are produced annually at animal feeding operations, located primarily in the eastern part of the state. Large emissions of ammonia (NH₃) gas and other trace gases emanate from the handling of animal wastes at these operations, NH₃ can contribute to the formation of fine particulate matter (PM_{2.5}) around the state causing regional haze events along with human health effects such as respiratory illnesses and premature death. The objective of this research is to provide the relationship between ammonia from these agricultural farms and its effect on PM_{2.5} concentrations. Satellite derived ammonia and aerosol optical depth (AOD) values were used as a way to mitigate issues with the spatial distribution of ground-based measurement. A multiple linear regression model was derived to predict ground level PM_{2.5} for a site in Cumberland County, North Carolina, and a site in Johnston County, North Carolina during the summer months (June, July and August) from 2008-2017. The model was created using the AOD retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASA's Aqua satellite along with surface PM_{2.5} monitor used by the Environmental Protection Agency and the North Carolina Department of Environmental Quality. The ammonia data used in the model was obtained through the Infrared Atmospheric Sounding Interferometer (IASI) located on board the MetOp-A satellite. The model also incorporated ground based metrological data as it has a significant impact on PM_{2.5} concentrations. The model was then utilized to predict PM_{2.5} concentrations in New Hanover County, Catawba County and Sampson county. A combination of the Cumberland county model and the Johnston county

model for the summer was chosen and validated for Duplin County, NC. The model is being used to predict Sampson County, NC, concentrations. The model predicted a total of six 24-hour exceedances over the nine-year period. This indicates that there are areas of the state that could have air quality issues that are not captured due to there not being a monitor. Separately, the idea of investigating ammonia control as a PM_{2.5} reduction strategy could be useful in areas dominated by or near high agricultural activity.

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Fine Particulate Matter (PM_{2.5}) Pollution in Intensive Agricultural Region of North Carolina:
Satellite Analysis and Integrate Ground-based Measurements

By

Rebecca Diane Wiegand

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APPROVED BY:

Dr. Viney P. Aneja
Committee Chair

Dr. Stacy A. Nelson

Dr. Anantha Aiyyer

Dr. William H. Battye
External Member

DEDICATION

This thesis is dedicated to my sister Christina. Thank you for being my confidant, my supporter and the one I can vent to, cry to and laugh with. You understood all the trials and never let me forget that there was a light at the end of the tunnel.

BIOGRAPHY

Rebecca Wiegand was born in Kalamazoo, Michigan on May 1st, 1994 to parents Paul Wiegand and Teresa Wiegand and siblings Christina and Daniel. Soon after the family moved to Corvallis, Oregon where they lived for 9 years until relocating to Holly Springs, North Carolina in 2004. As a child she was very active, playing soccer, baseball, basketball and participating in dance for eight years

She graduated in 2012 from Holly Springs High School and attended the University of North Carolina at Asheville to pursue her Bachelor of Science degree in Atmospheric Science with a concentration in Weather Forecasting and a minor in Mathematics. After graduating in 2016 she came to North Carolina State University to pursue a Master of Science in Atmospheric Science. While at North Carolina State she interned for two summers at North Carolina Department of Environmental Quality in the Division of Air Quality.

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Chapter 1: Introduction

1.1. Background

The eastern region of North Carolina has uniform terrain with few cities and large wide-open space. This area has become a highly populated with thousands of agricultural farms, housing mainly poultry and hogs (Aneja et al., 2008c). Because of this, North Carolina ranks as the 4th state in the United States for hog production; and the number one state for all poultry production combined because of NC strong turkey presence (Ross 2017). To put this into perspective, during 2016 in Duplin and Sampson Counties alone there were over 4 million hogs and 100 million chicken (North Carolina Agricultural Statistics 2017). These animals are raised in what is referred to as animal feeding operations (AFOs), which house hundreds to thousands of animals in a relatively small area. These AFOs appear all over the state and are a large driver of the state economy. Brands like Smithfield Foods and Tyson have farms located in the state bringing in billions of dollars to local farmers and the state's economy in general (North Carolina Agricultural Statistics 2017). However, along with being an economic driver in the state, these farms come with their fair share of problems.

The problems associated with the increases in agricultural development have been seen in North Carolina since the 1990s. Specifically, in 1997 the general assembly of North Carolina passed House Bill 515 (1997) which outlines the moratoria on construction or expansion of swine farms. This bill acted to prevent the addition of hog farms and lagoons or the expansion of existing hog farms and lagoons in the state citing the importance of providing clean water within the environment as the driver for this bill. The bill also addresses the odors that come from the operations themselves. Within the bill an economically feasible odor control strategy should be put into place to mitigate effects felt by the general public in the vicinity of these hog farms and

lagoons. More recently in Duplin County, which has one of the highest concentrations of agricultural farms in the state, several lawsuits discussing odor issues with these houses have been discussed and debated. Citizens in the county have been complaining about the odor emitted from these houses for years and a few civil lawsuits have been filed against big companies like Smithfield Foods. The lawsuits argue that the presence of the farm in the region is a nuisance to the citizen, contributes to decreased property values and decreased quality of life because of the odor and their proximity to these AFOs. The odor which has been the subject of these lawsuits and portion of HB 515 is the result of the main pollutant released from the animal waste, i.e. ammonia.

1.2. Ammonia

Ammonia (NH_3), a chemically reduced form of reactive nitrogen, is a commonly released pollutant from AFOs, accounting for more than half of the reactive nitrogen released into the environment (Galloway., 2003). The largest emitter of NH_3 into the atmosphere is from agricultural sources (Faulkner and Shaw, 2008), and furthermore almost 70% of global ammonia emissions are from anthropogenic sources such as biomass burning, fertilizers and animal waste (Vitousek et al., 1997). Specifically, in North Carolina, agricultural sources make up about 80% of the total ammonia emissions in the state and account for 40% of total nitrogen emissions (Wu et al., 2008). The breakdown of specific NH_3 emission sources in North Carolina can be seen in Figure 1, which shows that the hog population in North Carolina accounts for almost half of the total NH_3 emissions as of 1996. NH_3 plays a large role in the biogeochemical nitrogen cycle as it reacts within plants to produce nitrites and nitrates to further help produce atmospheric nitrogen (Vitousek et al., 1997; Erisman et al., 2007; Wing and Wolf, 2008; Sutton et al., 2013; Battye et

al., 2017). NH_3 also has several human health effects including eye, nose and throat irritation, dizziness and headaches (Schiffman, 1998; Wilson and Serre, 2006).

Once NH_3 is emitted from the AFOs, its fate in the atmosphere can be a few different paths. Figure 2 illustrates these various paths that trace gases, such as NH_3 , can take in the atmosphere from emission to transport and chemical reactions. One of the paths often seen is deposition to water bodies. NH_3 is a soluble gas and is commonly scavenged by rainfall or moisture in the atmosphere. Once it has deposited into water bodies, either via direct deposition i.e. dry deposition, or in the form of precipitation or fog, the water body is then subject to environmental issues ((Bittman and Mikkelsen, 2009; Aneja et al., 2008d). For example, NH_3 deposition into water bodies can lead to detrimental impacts in water through a process called eutrophication. Eutrophication is caused by excess nitrogen producing surface algal blooms that prevent plant life below the surface from photosynthesizing. This leads to low oxygen levels in the water which is harmful to the aquatic life, plant life, and the water body itself (Aneja et al., 2008a, 2008b; Stevens and Aneja, 2008, Linker et al., 2013). The waste that is produced by the animals is also frequently used as fertilizer and spread on crops throughout the farm, further releasing the pollutant into the atmosphere. As stated previously, once in the atmosphere NH_3 can react with other chemicals to create different pollutants. NH_3 being the most abundant base in the atmosphere has a large effect on the creation and general acidity of acid rain (Warneck, 1988) as well as the acidity level of clouds (Li and Aneja, 1992) and atmospheric aerosols (Lefer et al., 1999). NH_3 can also react with many pollutants already in the atmosphere or pollutants that are being emitted from nearby locations such as power plants or vehicles. One of the common reactions seen in the atmosphere involving NH_3 is the creation of particulate matter.

1.3. Particulate Matter

Particulate matter is a common pollutant seen in the atmosphere that can cause severe human health and environmental effects. Particulate matter can be released through primary sources (i.e. power plants and other industrial sources) and can be a secondary pollutant. This means that compounds can react in the atmosphere to produce particulate matter (Seinfeld and Pandis, 2016). Specifically, primary particulate matter compounds are typically elemental carbon, organic carbon, ash, sulfate and soil dust are common primary sources of particulate matter. Secondary sources of particulate matter are organic carbon, sulfate, nitrate and ammonium. These compounds are secondary sources because they are formed through gas phase oxidation of sulfur dioxide, nitrogen dioxide, volatile organic compounds (VOCs) or ammonia (Goetz et al., 2008). When inhaled, particulate matter can cause respiratory issues, heart problems and has been linked to premature death (Kampa and Castanas, 2008; Pui et al., 2014; Kravchenko et al., 2018). In terms of environmental health effects, fine particulate matter (define as particulate that have an aerodynamic diameter smaller than 2.5 microns), which is the most common type of particulate matter created through ammonia reactions, can lead to decreased visibility across large areas as well as localized haze events.

For this study, focus is on the reactions involving ammonia. Ammonia released into the atmosphere some commonly react with oxidation products of either sulfur dioxide (SO_2) or nitrogen oxide ($\text{NO}_x = \text{NO} + \text{NO}_2$) to produce ammonium sulfate and ammonium nitrate and thus these compounds are the most common form of ammonia based particulate matter (Li et al., 2008; McCubbin et al., 2002). However, to reduce particulate matter across the United States, the focus has previously been on the reduction of SO_2 from power plants and improving our vehicle emissions to reduce NO_x (Pinder et al., 2007).

The North Carolina Clean Smokestacks Act (2001) has reduced sulfur dioxide emissions by 89% compared to 1998 emissions (Implementation of the “Clean Smokestacks Act”, 2014). Furthermore, improved regulations on vehicle manufactures has helped to reduce NO_x emissions. Because these reductions have already been made, any additional effort to reduce both SO₂ and NO_x emissions would become increasingly less cost effective. Thus, some studies have started to indicate that a reduction in ammonia emissions would be a more cost-effective solution in terms of long-term reductions in fine particulate matter concentrations, at least in areas of high agricultural activity (Gong et al., 2013; Stokstad., 2014; Wu et al., 2016; Zhao et al., 2017; Guo et al., 2018). However, any reduction in particulate matter must be measured at monitoring stations. This leads to economic, political and logistical problems.

1.4. Monitoring Methods and Issues

Ammonia is a pollutant that is measured in North Carolina by passive monitors, however the locations of these monitors is sparse, seen in Figure 3. Majority of the monitors located in the state are maintained by the National Atmospheric Deposition Program (NADP) Ammonia Monitoring Network (AMoN). These monitors are passive diffusion type sensors measuring atmospheric ammonia averages over a two-week period (Ammonia Monitoring Network Site Operations Manual). This means that the monitor measures the concentration of ammonia in the air that flows around and through the sensor. They also measure the wet deposition of ammonia, meaning the concentration in precipitation. Despite most of the monitors being in place since 2010, the temporal scale in which they reported measurements as well as the spatial scale issues made them difficult to use for this study.

Particulate matter is measured throughout the state with monitors placed and maintained by the Environmental Protection Agency (EPA) and the North Carolina Department of

Environmental Quality (NCDEQ). The monitor used in North Carolina is an active monitor that takes in a predetermined amount of air and pulls it through a filter within the sensor. After 24 hours the filter is then taken out of the sensor and gravimetrically measured and the mass concentration in $\mu\text{g}/\text{m}^3$ is reported (Quality Assurance Project Plan Particulate Matter 2.5). The location of these monitors is primarily based on the location of population centers and thus due to the location of the monitors, areas heavily influenced by agricultural farms are often not measured directly by a monitor. In order to achieve the spatial resolution needed to accurately monitor $\text{PM}_{2.5}$ reductions throughout the state satellite data can be utilized. Satellites will allow us to obtain both the spatial and temporal data needed to accurately determine if there is a relationship between ammonia emissions from agricultural farms in Eastern North Carolina and high ground-level $\text{PM}_{2.5}$ concentrations. Satellite data can also be used to predict $\text{PM}_{2.5}$ concentrations in areas with a high agricultural influence.

1.5. Remote Sensing

Since the 1960s the National Aeronautics and Space Administration (NASA) has been launching satellites into orbit for a variety of reasons and applications. With almost 1,000 active satellites in orbit (Dunbar, 2018) earth is being monitored constantly for changes in terrain, forest density, ice sheet changes, atmospheric aerosols and various weather phenomena. In terms of air quality monitoring satellite data is a relatively new data source (Cheng et al., 2012; Battye et al., 2016; Bray et al., 2017). These satellites can be extremely useful in capturing a relatively high-resolution (such as 0.25° by 0.25° or 1 km by 1 km) air quality image over the entire world for a single day or multiple days. The temporal scale of satellite data is highly dependent on the orbiting path of the satellite. Generally, there are two different paths a satellite orbits around, either geostationary or polar. Geostationary satellites are placed around 35,800 km above the

earth's surface at the equator as they orbit at the same rate of motion so that the same area on earth is monitored constantly (ESA 2017). Polar orbiting satellites on the other hand orbit around the earth starting at the poles at around 200-1,000 km above earth's surface (ESA 2017). This orbit will typically follow the path of the sun, so that the images captured are visible images, typically referred to as a sun-synchronous orbit. Temporal scales of polar orbiting satellites normally range from a day or two to once a week or once over two weeks. One of the most common uses for either geostationary satellite or polar orbiting satellites is to monitor and measure phenomena in areas that are either not accessible or are not monitored by sensors or radars.

For these reasons, satellite data can be especially useful in rural or mountainous areas around the state. These rural areas are commonly where the agricultural farms are, and it is typically where monitoring networks are scarce due to a lack of population density. Using satellite data will allow us to develop a method for predicting ground level $PM_{2.5}$ concentrations in areas of high agricultural influence which normally do not have a ground-based measurement site. By utilizing satellite derived ammonia concentrations and aerosol optical depth (AOD) along with meteorological parameters we can predict, with reasonable certainty, $PM_{2.5}$ concentrations across North Carolina.

Chapter 2

Fine Particulate Matter (PM_{2.5})-Pollution and Ammonia (NH₃) Deposition in Rural Regions of North Carolina: Integrated Ground Based Measurement and Satellite Analysis

Rebecca D. Wiegand^{a,*} (rdwiegand@ncsu.edu), William H. Battye^a (whbattye@ncsu.com), Casey D. Bray^a (cdbray@ncsu.edu), and Viney P. Aneja^a (vpaneja@ncsu.edu)

Abstract

Intensive animal agriculture is an important part of North Carolina's economy. About ~ 10 million hogs, and 1 billion chickens and turkeys are produced annually at animal feeding operations, located primarily in the eastern part of the state. Large emissions of ammonia (NH₃) gas and other trace gases emanate from the handling of animal wastes at these operations, NH₃ can contribute to the formation of fine particulate matter (PM_{2.5}) around the state causing regional haze events along with human health effects such as respiratory illnesses and premature death. The objective of this research is to provide the relationship between ammonia from these agricultural farms and its effect on PM_{2.5} concentrations. Satellite derived ammonia and aerosol optical depth (AOD) values were used as a way to mitigate issues with the spatial distribution of ground-based measurement. A multiple linear regression model was derived to predict ground level PM_{2.5} for a site in Cumberland County, North Carolina, and a site in Johnston County, North Carolina during the summer months (June, July and August) from 2008-2017. The model was created using the AOD retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASA's Aqua satellite along with surface PM_{2.5} monitor used by the Environmental Protection Agency and the North Carolina Department of Environmental Quality. The ammonia data used in the model was obtained through the Infrared Atmospheric Sounding Interferometer (IASI) located on board the MetOp-A satellite. The model also incorporated ground based meteorological data as it has a significant impact on PM_{2.5} concentrations. The

model was then utilized to predict PM_{2.5} concentrations in New Hanover County, Catawba County and Sampson county. A combination of the Cumberland county model and the Johnston county model for the summer was chosen and validated for Duplin County, NC. The model is being used to predict Sampson County, NC, PM_{2.5} concentrations. The model predicted a total of six 24-hour exceedances over the nine-year period. This indicates that there are rural areas of the state that could have air quality issues that are not captured due to there not being a monitor. The dry deposition of ammonia to the surface using IASI measurements was estimated to be around 7.35 kg/ha/season in Sampson county compared to wet deposition of ammonium which is 1.96 kg/ha/season during the summer of 2011. Furthermore, dry deposition of ammonia was higher than wet deposition of ammonium at all nine locations in which measure wet deposition.

1. Introduction

The eastern region of North Carolina has uniform terrain with few cities and a large amount of wide-open space. This area has become a highly populated with thousands of animal agricultural farms housing mainly poultry and hogs (Aneja et al 2008c). North Carolina ranks as the 4th state in the United States for hog production, and the number one state for all poultry production combined because of NC's strong turkey presence (Ross 2017). During 2016 Duplin and Sampson Counties (in Eastern NC) alone there were over 4 million hogs and 100 million chicken (North Carolina Agricultural Statistics 2017). These animals are kept in what is referred to as animal feeding operations (AFOs), which can house hundreds to thousands of animals in a relatively small area. Animal agriculture is a large driver of the state's economy. However, animal agriculture along with being an economic driver in the state, these farms come with their fair share of problems.

Ammonia (NH_3), a chemically reduced form of reactive nitrogen, is a commonly released pollutant from these AFOs, accounting for more than half of the reactive nitrogen released into the environment (Galloway, 2003). The largest emission source of NH_3 into the atmosphere is from agricultural sources (Faulkner and Shaw, 2008). NH_3 plays a significant role in the biogeochemical nitrogen cycle and causes some health and environmental effects (Erisman et al., 2007; Wing and Wolf, 2008, Sutton et al., 2013; Battye et al., 2017). For example, ammonia deposition into water bodies can lead to detrimental impacts like eutrophication. Eutrophication is caused by excess nitrogen in water bodies producing surface algal blooms that prevent plant life below the surface from photosynthesizing. This leads to low oxygen levels in the water which is harmful to the aquatic life, plant life, and the water body itself (Aneja et al., 2008a, 2008b; Stevens and Aneja, 2008, Linker et al. 2013). The manure that is produced by the

animals is frequently used as fertilizer and spread on crops throughout the farm, further releasing the pollutant into the atmosphere. NH_3 also has a number of human health effects including eye, nose and throat irritation, dizziness and headaches (Schiffman, 1998; Wilson and Serre, 2006). Once NH_3 is released into the atmosphere it can then deposit by either rainfall or dry deposition to regional waterbodies or it can react with other compounds in the area to create other pollutants and cause further harm (Bittman and Mikkelsen, 2009; Aneja et al., 2008d;). One of the common reactions seen in the atmosphere involving NH_3 is the creation of fine particulate matter (i.e. gas-to-particle conversion).

Particulate matter is a common pollutant seen in the atmosphere that can cause severe human health and environmental effects. When inhaled, particulate matter can cause respiratory issues, heart problems and has been linked to premature death (Kampa and Castanas 2008; Pui et al., 2014, Kravchenko et al., 2018). Fine particulate matter (define as particulate matter that have an aerodynamic diameter smaller than 2.5 microns) can lead to decreased visibility across a large area as well as localized haze events. Particulate matter can be released through primary sources (i.e. power plants and other industrial sources) and can be a secondary pollutant (reactions between other chemicals creating a third pollutant). This means that compounds can react in the atmosphere to produce particulate matter (Seinfeld and Pandis 2016). For this study, we focus on the reactions involving ammonia. Ammonia released into the atmosphere may react with oxidation products of either sulfur dioxide (SO_2) or nitrogen oxide (NO_x) ($\text{NO}_x = \text{NO} + \text{NO}_2$) to produce ammonium sulfate and ammonium nitrate (Li et al. 2008). Both of these compounds are considered particulate matter and can have any number of human or environmental health effects. However, to reduce particulate matter across the United States, the

focus has been on the reduction of criteria pollutants, such as sulfur dioxide and oxides on nitrogen (NO_x) (Pinder et al., 2007).

The North Carolina Clean Smokestacks Act (2001) has reduced sulfur dioxide emissions by 89% compared to 1998 emissions (Implementation of the “Clean Smokestacks Act”) and the improved regulations on vehicle manufactures has helped to reduce NO_x emissions. Because these reductions have already been made, any additional effort to reduce both SO₂ and NO_x emissions would become less cost effective. Thus, some studies have started to indicate that a reduction in ammonia emissions would be a more cost-effective solution in terms of long term reductions in particulate matter concentrations (Gong et al., 2013; Stokstad, 2014; Wu et al., 2016; Zhao et al., 2017; Guo et al., 2018). However, ammonia is not a criteria pollutant. Moreover, any reduction in particulate matter must be measured at monitoring stations. This leads to economic, political and logistical problems.

Ammonia is directly measured in North Carolina by passive monitors, however the locations of these monitors is sparse. Moreover, particulate matter is measured at various locations throughout the state with monitors placed and maintained by the Environmental Protection Agency (EPA) and the North Carolina Department of Environmental Quality (NCDEQ). The location of these monitors (Figure 4) is widespread throughout the state and lacks the ability to monitor at a high spatial resolution. In order to achieve the spatial resolution needed to accurately monitor PM_{2.5} reductions throughout the state satellite data may be utilized. Satellites allow us to obtain both the spatial and temporal data resolution needed to accurately determine if there is a relationship between ammonia emissions from agricultural farms in Eastern North Carolina and PM_{2.5} concentrations. Satellite data can also be used to predict PM_{2.5} concentrations in areas with a high agricultural trace gas emissions.

Satellite data is a relatively new data source in air quality monitoring (Cheng et al. 2012; Battye et al., 2016; Bray et al., 2017, Aneja et al., 2017). These satellites can be extremely useful in capturing a relatively high-resolution (such as 0.25° by 0.25° or 1 km by 1 km) air quality image over the entire world for a single day or multiple days. For this reason, satellite data can be especially useful in rural areas around the state. These rural areas are commonly where the agricultural farms are, and it is typically where monitoring networks are scarce. Using satellite data will allow us to develop a method for predicting ground level $PM_{2.5}$ concentrations in areas of high agricultural influence which normally do not have a ground-based measurement site. By utilizing satellite derived ammonia concentrations and AOD along with meteorological parameters we can predict, with reasonable certainty, $PM_{2.5}$ concentrations across North Carolina.

2. Data and Methodology

2.1. Location Description

North Carolina ranks as fourth nationally in terms of production of hogs and ranks number 1 in poultry (North Carolina Agricultural Statistics 2017). With almost 10 million hogs, and 1 billion chickens and turkeys, pollutants from these farms are a source of conversation in the legislature in the state. In 1997, House Bill 515 placed a moratorium on the creation or expansion of hog farms in the state, citing the Clean Air Act and the Clean Water Act as reasons for the restriction (HB 515). Recently in Eastern North Carolina, many residences of these high agriculturally activity counties have started filing nuisance lawsuits against large hog farms. These nuisance lawsuits detail odor issues and a general decrease in quality of life for those in the area. For these reasons our study focuses on various areas in North Carolina, all of which, due to proximity and wind direction, will have a direct influence from these farms. This ultimately will allow for further understanding of how these agricultural areas affect ground level PM_{2.5} concentrations.

2.2. Satellite Derived Ammonia Data

Satellite derived ammonia retrievals from the Infrared Atmospheric Sounding Interferometer (IASI) from 2008 through 2017 were used. IASI is a collaboration between the European Organization for the Exploitation of Meteorological Satellites and the National Centre for Space Studies (CNES) or the French government space agency. IASI was launched in 2006 on the MetOp-A satellite and is a polar orbiting sun synchronous satellite with an orbit altitude at around 817 km above the earth's surface. IASI has an orbital period of about 90 minutes, crossing the equator at around 9:30 AM and PM local time, with each subsequent pass displaced by about 22.5 degrees of longitude. The satellite measures detailed infrared spectra over a broad

angular swath with a spatial resolution of about 12 km (Van Damme et al., 2015). IASI researchers retrieve estimated total atmospheric column loadings of NH_3 and other pollutants based on patterns of infrared absorption. Specific information on the development and comparison testing of the algorithm used to derive ammonia measurements is seen in both Van Damme et al. (2014) and Van Damme et al. (2015).

At the latitude of North Carolina, morning and evening measurements are collected at about 10 a.m. and 10 p.m. local time. For this study, we used the morning pass to perform the analysis because NH_3 concentrations are typically higher during this time. The data was filtered by the error estimate reported with the data. Only points that had an error less than 100% were used in this study. The data was obtained through the ESPRI Data Centre (<https://cds-espri.ipsl.upmc.fr/etherTypo/index.php?id=1700&L=1>)

2.3. Satellite Derived Aerosol Optical Depth

Satellite based 550 nm aerosol optical depth (AOD) retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) from 2008-2017 were used in this study. MODIS is onboard National Aeronautics and Space Administration's (NASA) Aqua and Terra satellites which, like IASI, are polar orbiting satellites. Aqua and Terra orbit at around 705 km above the earth's surface and pass North Carolina once per day. For this study, MODIS level 2, collection 6.1 high confidence AOD at 10 km x 10 km measurements from Aqua were used. Retrievals onboard the Aqua satellite was used specifically due to deterioration issues with the MODIS sensor on the Terra satellite (<https://mcst.gsfc.nasa.gov>, 2017). This data was obtained through the NASA's Goddard Space Flight Center Web interface to the Level 1 and Atmosphere Archive and Distribution System (LAADS) (<https://ladsweb.modaps.eosdis.nasa.gov/search/>). A visual example of this data can be seen in Figure 5. The blank location in the image can be

attributed to cloud cover over the area (Levy et al., 2010). Another reason for the blank locations in the image is the filtering process of the data. The data was filtered to only include best quality data, which NASA indicates is a quality assurance flag of 3.

2.4. Ground based $PM_{2.5}$

The ground based $PM_{2.5}$ data was obtain from the Environmental Protection Agency's (EPA) Outdoor Air Data website (<https://www.epa.gov/outdoor-air-quality-data/download-daily-data>). The air quality stations around the state are a collaboration between the EPA office in Research Triangle Park and North Carolina Department of Environmental Quality (NCDEQ). Two sites were chosen, one in Cumberland County (35.0414, -78.9531) and another in Johnston County (35.5908, -78.4619) as input data to develop the statistical model. These locations were chosen based on their proximity to high agricultural areas in North Carolina. The $PM_{2.5}$ data was available at each of those sites for 3-day intervals for 2008-2017. $PM_{2.5}$ data was then collected from a site in Duplin County (34.9548, -77.9608), New Hanover County (34.3642, -77.8386) and Catawba County (35.7289, -81.3656) to validate the model performance. $PM_{2.5}$ was the only particulate matter size incorporated into this study because PM_{10} only makes up around less then 20% of the measured PM concentrations in these locations.

2.5. Meteorology Data

Ground based meteorology data was obtained from the North Carolina State Climate Office for the entire study period from sites in Cumberland, Johnston, Duplin, Sampson, Catawba and New Hanover Counties. Daily averaged temperature in degrees Celsius ($^{\circ}C$), pressure in millibar (mb), wind speed in meters per second (m/s) and relative humidity in percent (%) where available from each station and used in the development of the model. Days with reported rainfall were excluded from the final analysis because they would lead to washout

events for both the ammonia and AOD data. Figure 6 shows the location of these sites, which for Cumberland, Johnston, Duplin, Catawba and New Hanover are collocated with the ground level PM_{2.5} sites. The figure also shows the counties with the high agricultural production as of 2017 and predominant wind directions to illustrate the agricultural influence on each of these areas is in Figure 7.

2.6. Methodology

IASI ammonia retrievals are filtered so that only those retrievals with a relative error less than 100% are used. AOD retrievals are filtered to use only those observations with the best quality rating (quality assurance flag = 3). The quality assurance flag is given by the algorithm team as their assessment of the data quality (Levy et al. 2015). These retrievals are then collocated with the ground level meteorology sites and the ground level PM_{2.5} sites. This is done through the averaging method (Cheng et al., 2012). In the averaging method, values within a 100 km radius of the PM_{2.5} ground site and the ground level meteorology station are averaged together to receive a single value for the time period, which in this study is one day. This process is repeated every day for the months of June, July and August, for the 9-year period. June, July and August were chosen because they would allow for the highest ammonia retrieval as, statistically; summer months have the highest ammonia concentrations in North Carolina. Days with reported rainfall are excluded from the analysis because this would result in a washout event for both the PM_{2.5} data and the ammonia data as they are typically scavenged by rainfall (Shimshock and De Pena, 2016, Aneja et al., 2017).

At the sites in Cumberland and Johnston counties, the data were then compiled for each day using averaged meteorology parameters and subsequently averaged by month. A multivariate regression model was run in the Statistical Analysis System (SAS) using the IASI

ammonia data, the MODIS AOD data and the meteorology data per month at both locations. We then tested the accuracy (i.e. validated) of our model using data from Duplin County. Once the model was tested, PM_{2.5} values were then predicted in Catawba County, New Hanover County and Sampson county to see the influence of agriculture on PM_{2.5} concentrations across the state and in different eco-regions.

Finally, to investigate the dry deposition of ammonia to the surface, we used the IASI column measurements to calculate deposition. To do this, we created a ratio to compare IASI column measurements to the NCDEQ Clinton ammonia monitoring sites ammonia concentrations. This ratio was then used as a way to convert the IASI column measurements to surface ammonia concentrations. The surface measurements were the averaged into a latitude and longitude grid over the state. The measurements are then multiplied by a deposition velocity to find ammonia dry deposition to the surface during the summer of 2011. The deposition velocity of 1.5 cm/s was used in this study as a average of commonly used deposition velocities found in the literature (Schrader and Brümmer 2014).

3. Results

Multiple linear regression models, as mentioned previously, were created to assess the ability of remotely sensed data to predict ground based $PM_{2.5}$ concentrations in rural areas that are usually characterized as having high agricultural activity and no ground based $PM_{2.5}$ monitor. The models were created for Cumberland and Johnston Counties in North Carolina and validated from Duplin County North Carolina against the ground-based measurements located in the county. Cumberland and Johnston counties were chosen specifically because of their proximity to Sampson county, which has the high agricultural activity in that state next to Duplin county, which was chosen as the validation site for this reason. Sampson County could not be used for validation because there is no ground based $PM_{2.5}$ monitor in the county. After reviewing and testing a few different models, a combination of Cumberland and Johnston county data for the entire summer period was chosen:

$$PM_{2.5} = EXP(15.14 + (1.05 \times 10^{-17} * Ammonia) + (1.51 * AOD) + (0.26 * T) + (-0.013 * P) + (-0.040 * WS) + (-0.013 * RH) \quad (1)$$

where Ammonia is the total atmospheric column loading of ammonia as retrieved from IASI observations, in molecules cm^{-2} , AOD is the MODIS aerosol optical depth, T is temperature in $^{\circ}C$, P is pressure in millibars, WS is wind speed in meters per second and RH is relative humidity in percent.

This model gave an r^2 value of 0.43. The specific statistics can be seen in Table 1 (an analysis of variance (ANOVA) table.) The table also shows the f statistic for our model. The values seen in the table indicate that our model was able to explain a significant portion of the data variation. Table 2 is a parameters estimate table produced by SAS. The table indicates the significance of a parameter based on the t statistic used in the model. For our model, the table

shows that AOD is the most significant variable in our model, followed by relative humidity, temperature and ammonia. The intercept is relatively significant while pressure and wind speed are the least significant. We know this because $P > F$ values have a significant range to them. Anything less than 0.01 has strong significance while anything between 0.01 to 0.05 has appreciable significances.

The results of the Duplin County prediction can be seen in figure 8. The figure shows four different scatter plots each representing a summer month (June, July and August) and a total graph that included all three months in one plot. These plots act to illustrate a visual representation of the model performance at this location. Table 3 illustrates the normalized mean bias (NMB) and normalized mean error (NME) values, which are commonly used to assess the performance of models (Boylan and Russell, 2009).

Once this model was verified for Duplin, it was then used to predict $PM_{2.5}$ concentrations in New Hanover and Catawba counties. These locations are also affected by high agricultural production areas, however, they have very different meteorological conditions and processes affecting them daily. The results of this analysis can be seen in Figures 9 and 10. Figure 9, shows results for New Hanover County and illustrates that despite the different meteorological mechanisms, the model can predict $PM_{2.5}$ concentrations for this area at a relatively high degree of accuracy. Table 4 shows the model prediction parameters used for this study and clearly shows the model's prediction struggle in July. This particularly high value is the result of the model's dependence on AOD values. A high AOD value will sometimes result in an overpredicted $PM_{2.5}$ value. Similarly, figure 10, shows results for Catawba County, however the model consistently under predicts concentrations at this location compared to both New Hanover and Duplin Counties, which can be seen in table 5. This indicates that the different

meteorological mechanisms that dominate in Catawba County are not well understood by the model. Catawba County is also at a different elevation than the other two locations, which could explain some of the inconsistent predictions. Overall, these results suggest that the multiple regression model is able to predict (at a relatively high certainty) for the eastern portion of North Carolina and loses some capabilities in the western portion of the state likely due to topography.

We then used the combination model to predict $PM_{2.5}$ values in Sampson county. As previously mentioned, Sampson county has one of the highest concentration of agricultural activity (both animal and crop) in the state. Due to its rural landscape, there is no $PM_{2.5}$ monitor available and thus, no $PM_{2.5}$ data for this location. Our model results showed, also seen in Figure 11, that the $PM_{2.5}$ concentrations are low; however, the model did indicate that six days out of the nine-year period were over the EPA NAAQS of $35 \mu\text{g m}^{-3}$. In order to further investigate how many exceedance the model predicted, the normalized mean error values calculated for New Hanover county were used to see how the model's error would affect the number of exceedances calculated. New Hanover county errors were used because they were the highest of the three errors calculated for the different counties. Given the errors in the model, the number of exceedances could range from ten to three during the nine-year period. This could indicate that areas near agricultural activity could see higher $PM_{2.5}$ values, most of which are not being capture due to monitoring locations. This could also suggest that a reduction in ammonia emissions could have a positive impact on $PM_{2.5}$ concentrations in these high agricultural areas.

Finally, we investigated the dry deposition of ammonia to the surface in North Carolina. From this we developed a series of maps to indicate where the deposition was occurring more frequently. In Figure 9, we can see a series of different maps, starting with the first image which depicts the aerosol optical depth, measured from the MODIS sensor for the summer of 2011.

Below this image is a map showing the IASI ammonia column concentrations and IASI surface concentrations calculated from the model data. Finally, the bottom image is the dry deposition calculated from the IASI surface ammonia concentrations. The figures show that the dry deposition most commonly occurs in the south eastern portion of the state, which lines up well with areas that have high agricultural emissions and high AOD retrievals. To further investigate dry deposition of ammonia, we compared the dry deposition of ammonia values we calculated with wet deposition of ammonium values retrieved from the National Trend Network, the results of which can be seen in Table 6. In the table, it can be seen that dry deposition values are greater across the state compared to the wet deposition values, however, are specifically high in Sampson, Carteret and Onslow counties. These locations make sense as Sampson county is the highest producer of ammonia emissions, along with Duplin county. Carteret and Onslow counties are located downwind of both Sampson and Duplin counties leading, in part, to elevated deposition values. Not only do these three counties have the largest dry deposition values, they also have some of the largest differences between the two types of depositions. Overall, the counties located in the southeastern portion of the state have higher dry deposition values compared to the western and central portions of the state.

4. Conclusion

We have created a multiple regression model that can predict $PM_{2.5}$ concentrations in counties with the highest agricultural activity in North Carolina. High agricultural activity results in high concentration of ammonia being released from agricultural farms. Ammonia is also a precursor to $PM_{2.5}$ formation and may cause an increase in $PM_{2.5}$ concentrations in these areas which could lead to poor air quality and quality of life for those living in the area.

This model was developed using remotely sensed data, making it resistant to issues in the scarcity of ground based $PM_{2.5}$ monitors around the state. Many of the areas around these agricultural farms are rural and have no monitor in place to track these concentrations on a daily basis. Satellite data, however, can introduce other limitations. For example, the instrument can not directly measure ammonia concentrations at the surface, the concentrations are calculated through an algorithm developed by researchers which introduces limitation on the accuracy of the concentrations from the satellite. The same issues can be said for the AOD data. Despite the limitations, satellite algorithms are improving over time and as they improve, utilizing this data will become more important. Satellite data can also be utilized for the meteorology data if ground based data isn't available. Modern-Era Retrospective analysis for Research and Applications (MERRA) data is globally modeled meteorological data based on GEOS-5 atmospheric data assimilation system. The data models ground based temperature, pressure and wind speed well. However the data does not contain relative humidity, thus it must be obtained experimentally or mathematically.

The model was developed for Cumberland and Johnston counties. The model was validated for Duplin county; and applied to predict $PM_{2.5}$ in New Hanover, Catawba and Sampson counties, all of which have a predominate influence from these agricultural farms. The

model predicted PM_{2.5} values in Sampson county that were above the National Ambient Air Quality Standard (NAAQS) limit of 35 $\mu\text{g m}^{-3}$. The need to investigate an ammonia reduction strategy due to its effects on PM_{2.5} concentrations in high agricultural areas is becoming more prevalent. If the PM_{2.5} reduction strategies seen in the past, such as the Clean Smokestacks Act and the Clean Air Act, have been as successful as they can be, therefore reducing ammonia emissions could provide not only air quality improvements but also a reduction in PM_{2.5} related issues.

When looking into the dry deposition of ammonia to the surface, we discovered a large area of ammonia deposition around the high agricultural regions. This could help indicate that NH₃ plays a significant role in overall atmospheric deposition (Li et al 2016). However, because of the lack of monitoring in these areas, this deposition isn't captured in these areas. Using remotely sensed data allowed us to look at these agricultural regions and further understand the spatial variability of atmosphere deposition as well as PM_{2.5} variability, which could then influence the future expansion of PM_{2.5} monitoring in agricultural locations. The use of remote sensing data could also help some of the uncertainty associated with spatial patterns of the deposition. As discussed previously, areas can be influenced by the transport of NH₃, which would lead to deposition to the surface occurring downwind of the NH₃ source, which is not currently being captured by monitoring networks around the state. Since PM_{2.5} is regulated under the EPA primary National Ambient Air Quality Standards (NAAQS) particularly close attention is paid to its components. Furthermore, for a regulatory context, NH₄⁺ is now increasingly important for the secondary NAAQS as a component of ecosystem exposure. Overall, nitrogen deposition, specifically NH₃ deposition in intensive agricultural areas is an

important area of study to further understand its spatial reach around the state and its impact on PM_{2.5}.

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Chapter 3: Conclusion and Future Work

A multiple linear regression model was created in two locations, Cumberland and Johnston counties, in Eastern North Carolina. These counties were chosen based on their proximity to areas with high agricultural emissions. The model was then tested for use in other areas of North Carolina to see how it predicted PM_{2.5} concentrations. During this study we tested four other locations, three in Eastern North Carolina and one in Western North Carolina and found that the model predicted concentrations well in all three areas of Eastern North Carolina and predicted concentration relatively poorly in western North Carolina. The variables within the model included ammonia retrievals from IASI, AOD retrievals from MODIS along with four meteorological variables, temperature, pressure, wind speed and relative humidity. The correlation ended up covering a statistically significant portion of the variability in PM_{2.5} concentrations, however there were some residual variability in which the model did not describe. Some of the residual variability might have been described by other meteorological factors such as solar radiation, because PM_{2.5} formation from ammonia is a photolytic reaction. Another reason could be that not all PM_{2.5} is ammonia based. Some is nitrate based or sulfate based, which would not be captured well by the model. Finally, some PM_{2.5} is not a secondary pollutant, some is emitted as a primary pollutant and these would not be captured well by the model.

In terms of future work, I would like to investigate testing more locations in eastern North Carolina. Since only three locations in eastern North Carolina were tested it would be beneficial to see additional predictions to further evaluate the model. Furthermore, two out of three of the locations chosen in eastern NC were directly influenced by these agricultural emissions while only one was influenced by the transport of emissions. I would like to test other locations around the eastern portion of the state that are not directly influence by the emissions

but are influenced by the transport of the emissions. These locations, such as Greenville or Washington, NC are often not considered as areas influenced directly by agricultural emissions, however due to predominate wind directions and other meteorological factors, these emissions could contribute to $PM_{2.5}$ concentrations in the area. Other areas near the north coast of the state often see regional haze events due to increased $PM_{2.5}$ concentrations. Some of these areas have agricultural emissions nearby, however they are also, like New Hanover County, influenced via transport of ammonia. Looking into the agricultural impact on $PM_{2.5}$ concentrations in these locations could give some insight on the regional haze issues in the area.

Another area of work that I would like to investigate is the model's issue predicting $PM_{2.5}$ concentrations in the western portion of the state. As previously mentioned, the model I developed had issues predicting $PM_{2.5}$ concentrations in Catawba County which is located on the western side of the state. It was theorized that the reason for this issue was a difference in meteorological parameters and elevation at the site. Catawba County is located very close to the Appalachian Mountains of North Carolina and due to this location, its meteorological influence will come from the mountains, unlike in the eastern portion of the state, where the model was built, which is influenced by the relatively flat land surrounding it or in the case of New Hanover County, an ocean breeze. This model issue is something I would like to look into more in order to further understand how to adjust the model setup. Adjusting this model would improve its performance in Catawba County and other mountainous regions of the state. This is important because during the summer, the mountains and ridgetops occasionally see elevated $PM_{2.5}$ according to state supported monitors in those regions. However, because that region of the state is mountainous, it is difficult to place monitors in that area.

Another possible explanation for the model's performance in Catawba County could be attributed to the difference in elevation. The elevation difference between the site in Catawba County and Cumberland County is around 282 meters or around 925 feet. This may have also played a role in the poor performance of the model in Catawba County. A further investigation in the effects of elevation on the model will help to indicate if this is an issue within the model's construction and furthermore, how the model can be adjusted to correct for elevation changes.

Finally, taking the methodology used in this study and applying it to other states that are known to have high concentrations of agricultural farms, such as Iowa, would be interesting to look into. Iowa, as of 2017, has around 20 million hogs throughout the state which is almost double the amount in North Carolina (Iowa Agricultural Statistics 2017). Because of the number of agricultural farms in Iowa, they are often seen having high ammonia emissions, similar if not higher than the emissions seen in North Carolina. It could be beneficial to take the methodology developed in this study and apply it to another state that also has high emissions. Iowa, as well as many other states including North Carolina, only has a select number of PM_{2.5} monitors in the state and they do not cover all of the state. These monitors, like in North Carolina, are placed in population centers which are not necessarily near the agricultural farms. The method of using remote sensed data to predict PM_{2.5} in areas that are either not populous enough for a monitor or are too remote could be a viable option for many states like Iowa with high agricultural emissions.

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Table 1: An analysis of variance table describing the amount of variance the model applies to chance and the amount it applies to the variables in the model.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	18.84	3.14027	38.99	<.0001
Error	309	24.88	0.08053		
Corrected Total	315	43.73			

Table 2: A parameter estimates for the model. This table describes each variable used in the model and its relative influence compared to other variables.

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	15.14	5.07	0.72	8.92	0.0030
Ammonia	1.05×10^{-17}	2.99×10^{-18}	0.98	12.21	0.0005
AOD	1.51	0.16	7.05	87.53	<.0001
Temp	0.26	0.007	1.06	13.14	0.0003
Pressure	-0.013	0.005	0.54	6.65	0.0104
WS	-0.04	0.02	0.38	4.75	0.0301
RH	-0.013	0.003	2.12	26.35	<.0001

Table 3: Normalized mean bias (NMB) and normalized mean error values (NME) for Duplin County by month.

Month	Normalized Mean Bias	Normalized Mean Error
June	0.47%	25.31%
July	13.19%	24.66%
August	14.59%	25.23%

Table 4: Normalized mean bias (NMB) and normalized mean error values (NME) for New Hanover County by month.

Month	Normalized Mean Bias	Normalized Mean Error
June	17.62%	28.55%
July	17.70%	43.61%
August	19.86%	28.04

Table 5: Normalized mean bias (NMB) and normalized mean error values (NME) for Catawba County by month.

Month	Normalized Mean Bias	Normalized Mean Error
June	-9.68%	23.92%
July	-13.19%	26.01%
August	-14.85%	27.10%

Table 6: Ammonia Dry deposition values calculated from IASI measurements during the summer of 2011 compared to ammonium wet deposition values measured from NTN monitors.

Site Number	County Location	Dry Deposition of Ammonia (kg/ha/season)	Wet Deposition of Ammonium (kg/ha/season)
NC03	Bertie	2.42	2.31
NC06	Carteret	6.26	1.05
NC25	Macon	3.94	0.65
NC29	Onslow	4.46	1.97
NC34	Rowan	3.79	1.36
NC35	Sampson	7.35	1.96
NC36	Scotland	3.43	1.13
NC41	Wake	2.07	1.26
NC45	Yancey	2.27	1.12

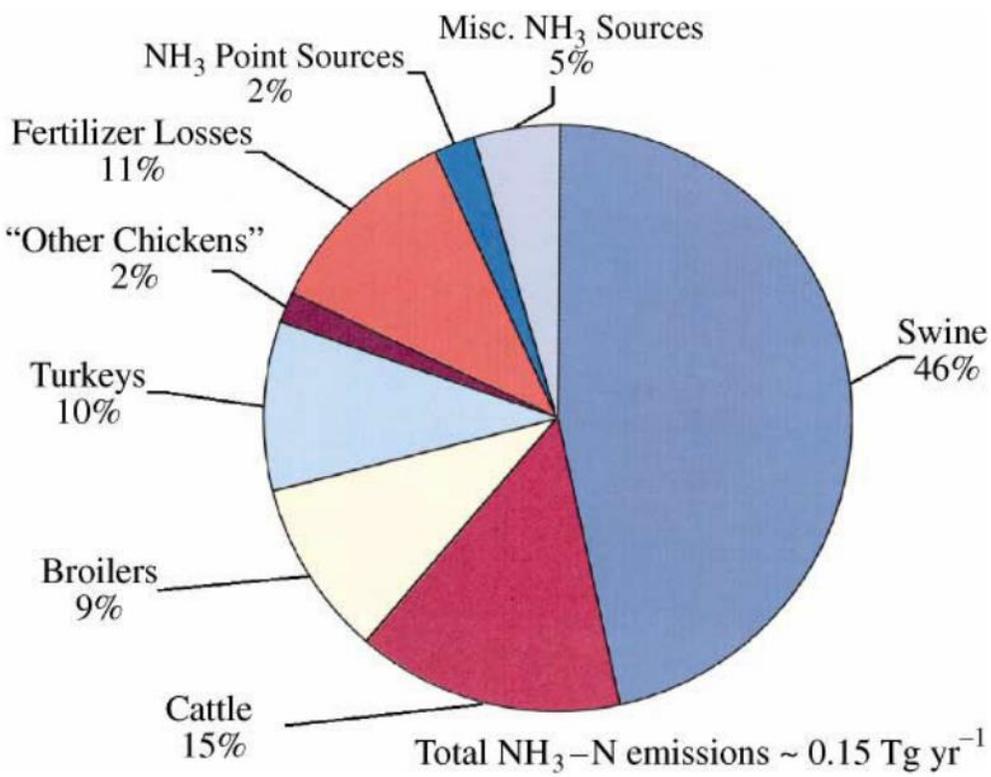
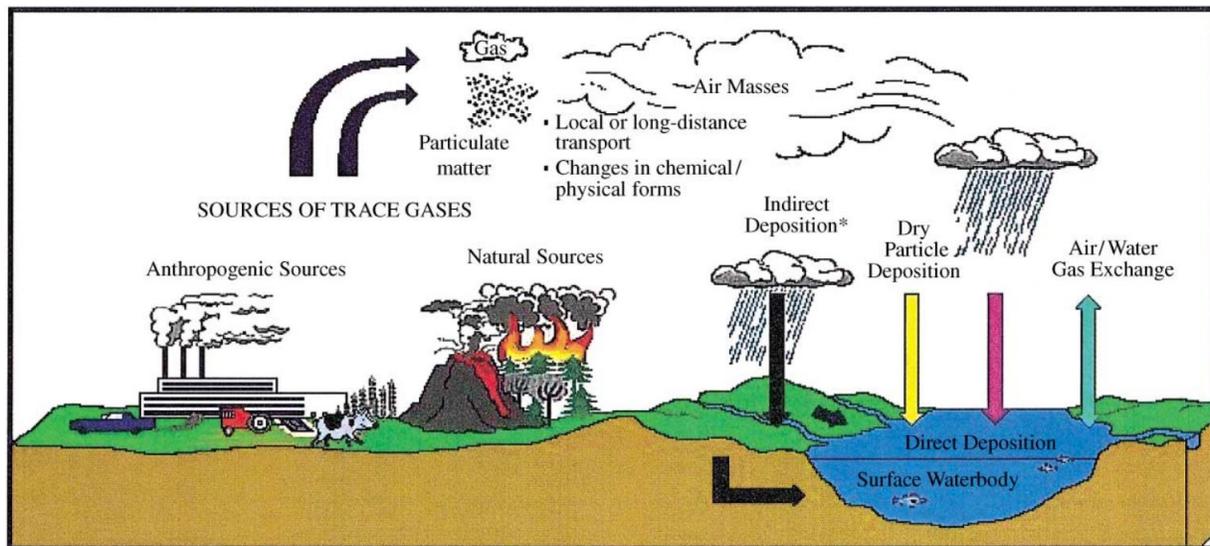


Figure 1. Percent of ammonia from various sources in North Carolina in 1996. (Source: Aneja et. al 1998)



* Indirect deposition is direct deposition to land followed by runoff or seepage through groundwater to a surface waterbody.

Figure 2. Ammonia sources and fate in the atmosphere. (Source: Aneja et. al 2001)

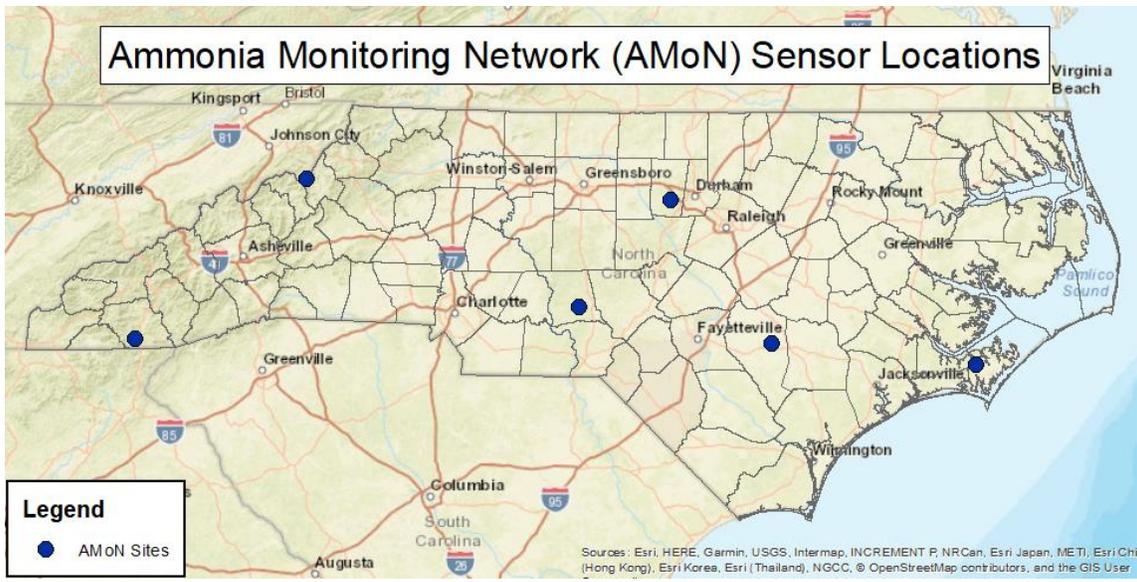


Figure 3. Ammonia Monitoring Network (AMoN) passive sensor locations. These are maintained by the National Atmospheric Deposition Program (NADP)

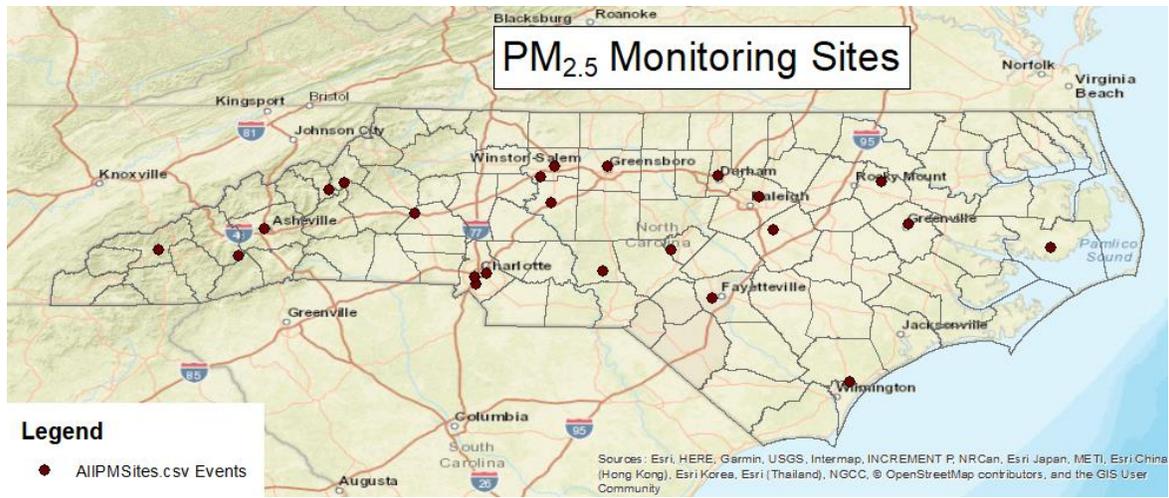


Figure 4. PM_{2.5} site locations. These sites are set up and maintained by the Environmental Protection Agency (EPA) and the North Carolina Department of Environmental Quality (NCDEQ).

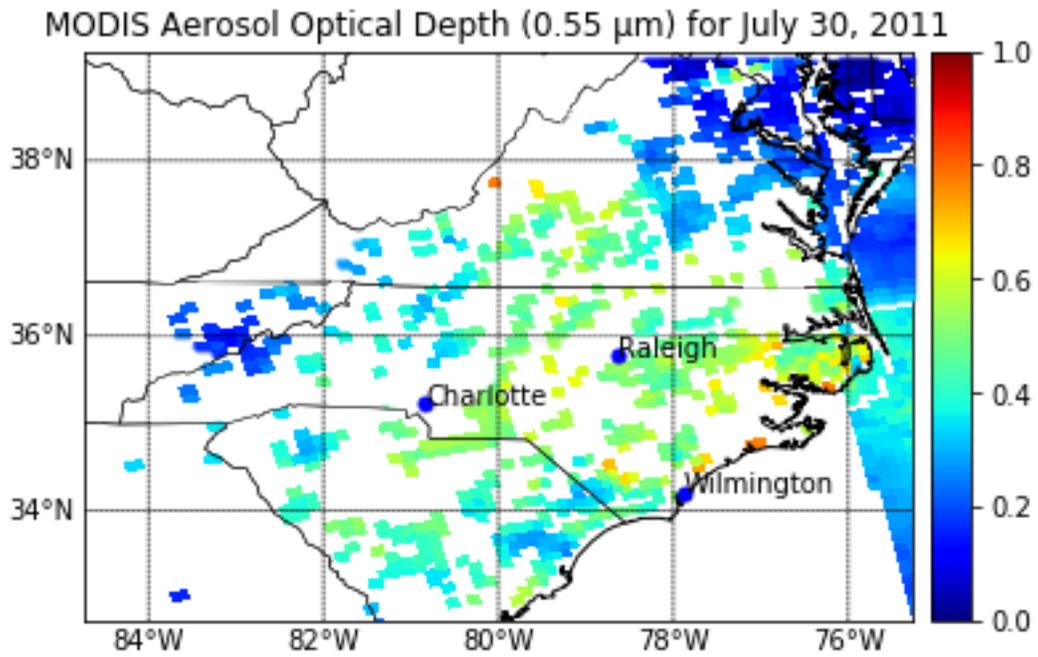


Figure 5. Aerosol Optical Depth (AOD) retrievals from the MODIS Aqua satellite for July 30th, 2011.

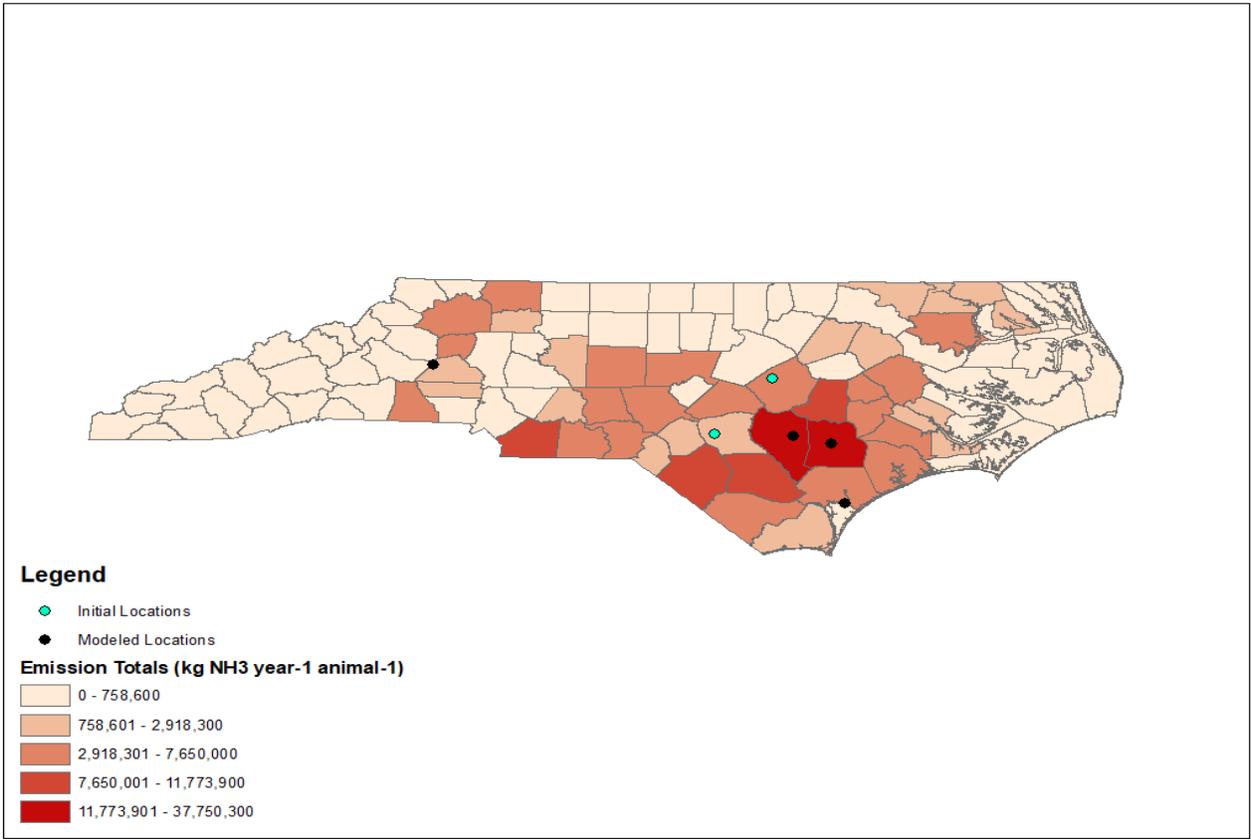


Figure 6. The initial locations that we developed the model from are seen in blue while the locations we modeled can be seen in black. Total ammonia emissions from agricultural farms is indicated by the shading.

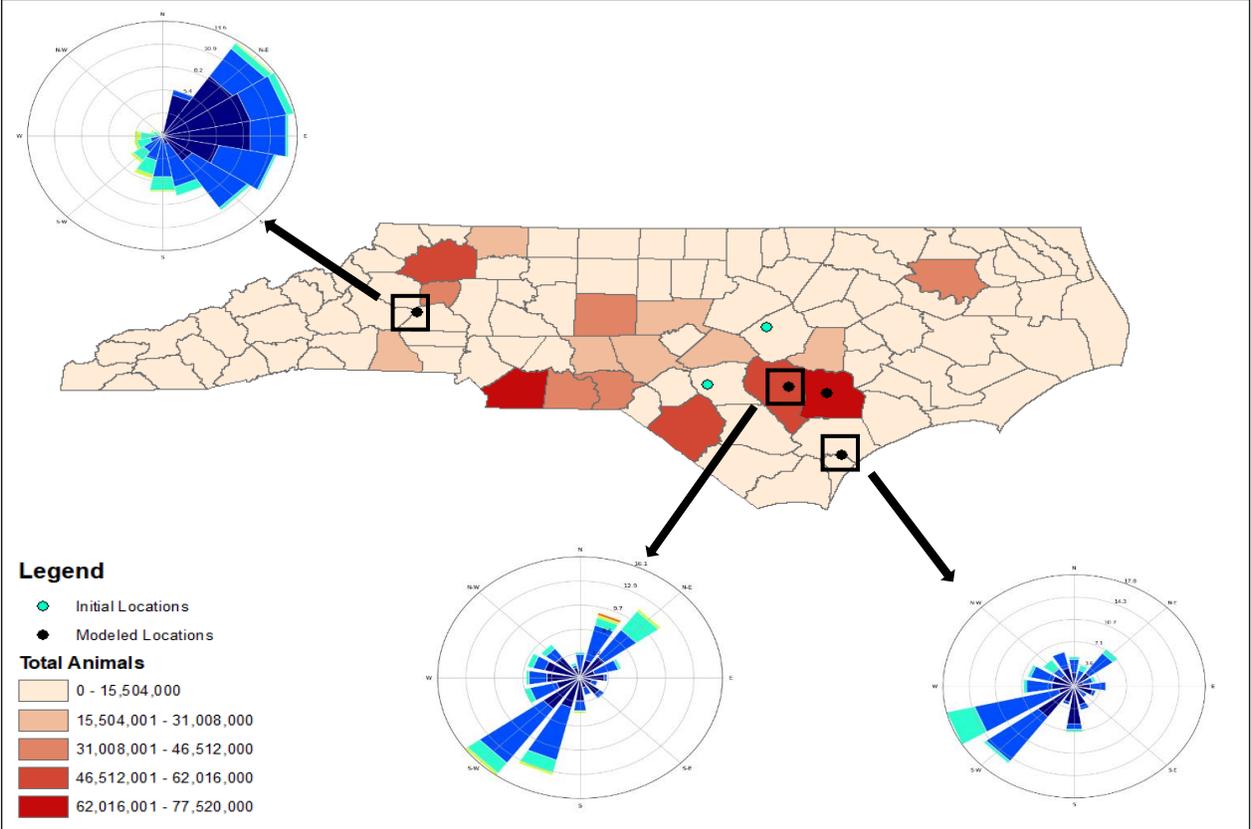


Figure 7. The initial locations that we developed the model from are seen in blue while the locations we modeled can be seen in black. Animal density is indicated by the shading and the wind roses are used to indicate the predominant wind direction and speed from three sites, New Hanover, Sampson and Catawba counties.

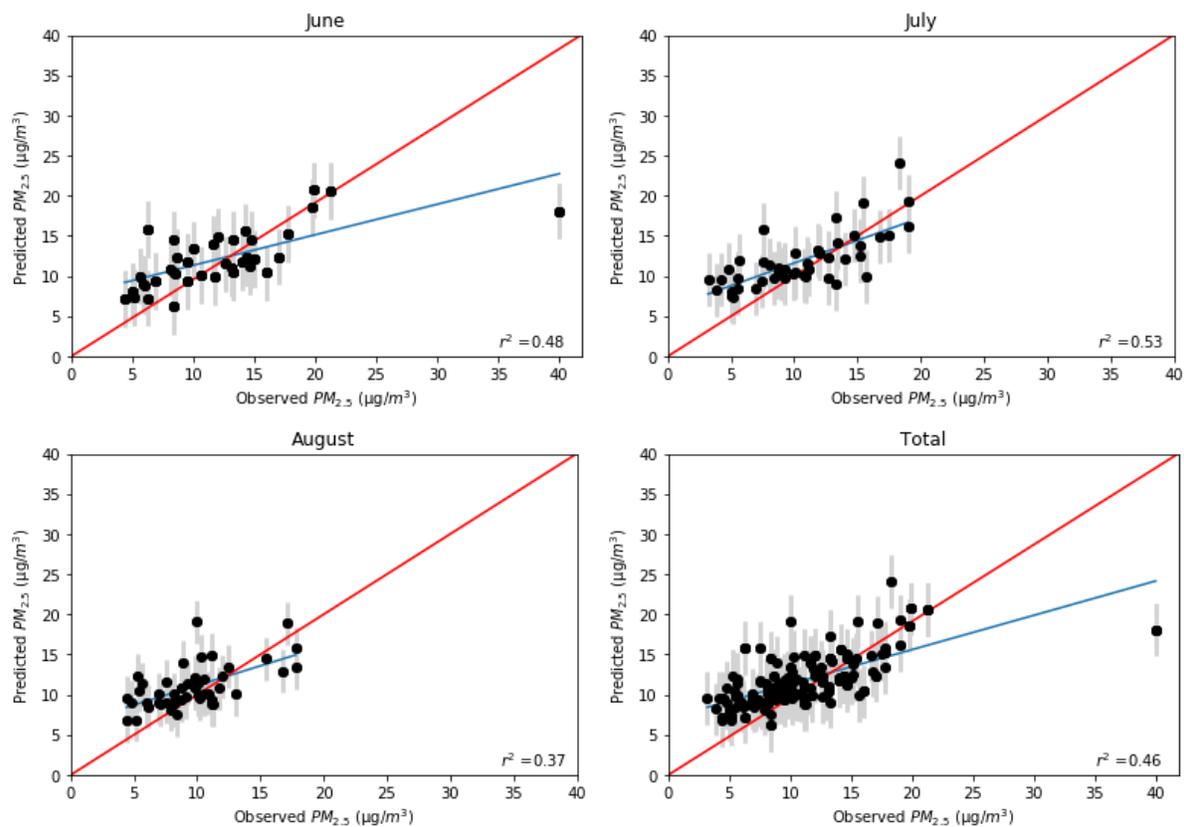


Figure 8. Scatter plots for Duplin county indicating model performance. The black points indicate the modeled versus predicted point, and the grey bars indicate the ± 1 standard deviation of the modeled dataset. The red line indicated the one to one line and the blue line is the best fit line for the data set.

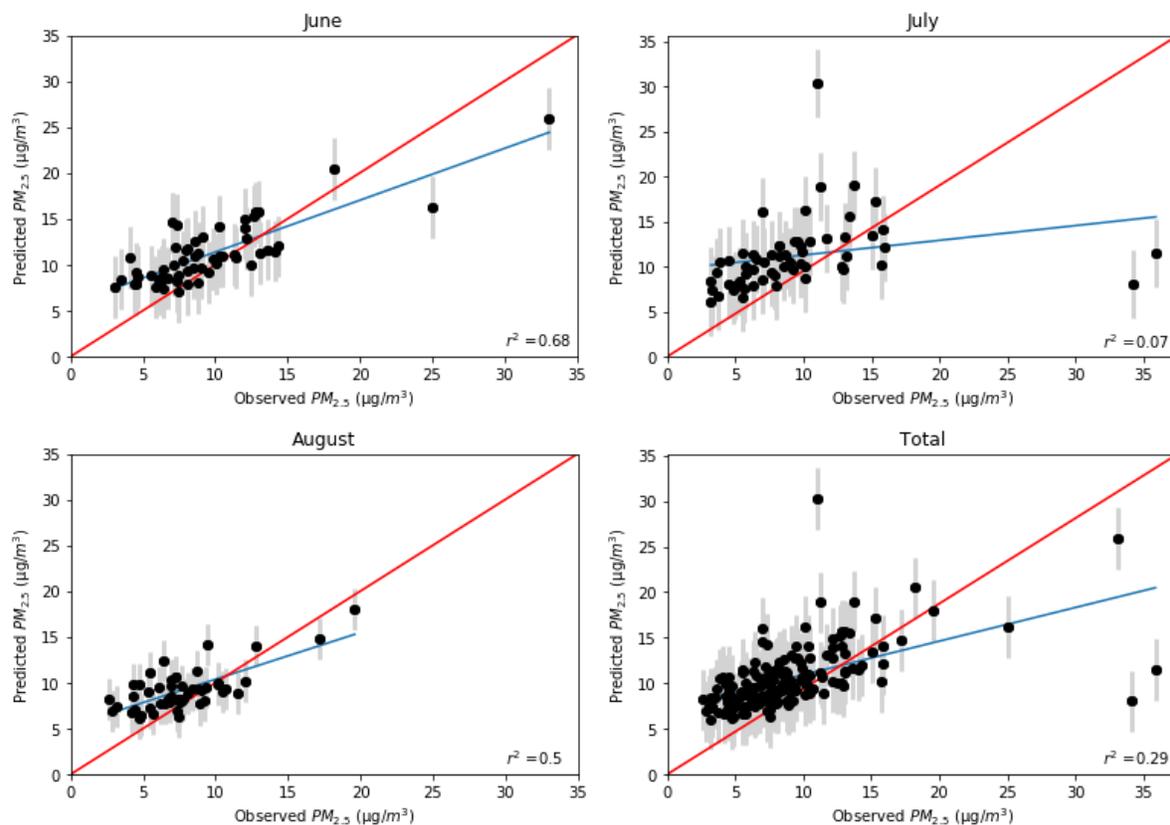


Figure 9. Scatter plots for New Hanover county indicating model performance. The black points indicate the modeled versus predicted point, and the grey bars indicate the ± 1 standard deviation of the modeled dataset. The red line indicated the one to one line and the blue line is the best fit line for the data set.

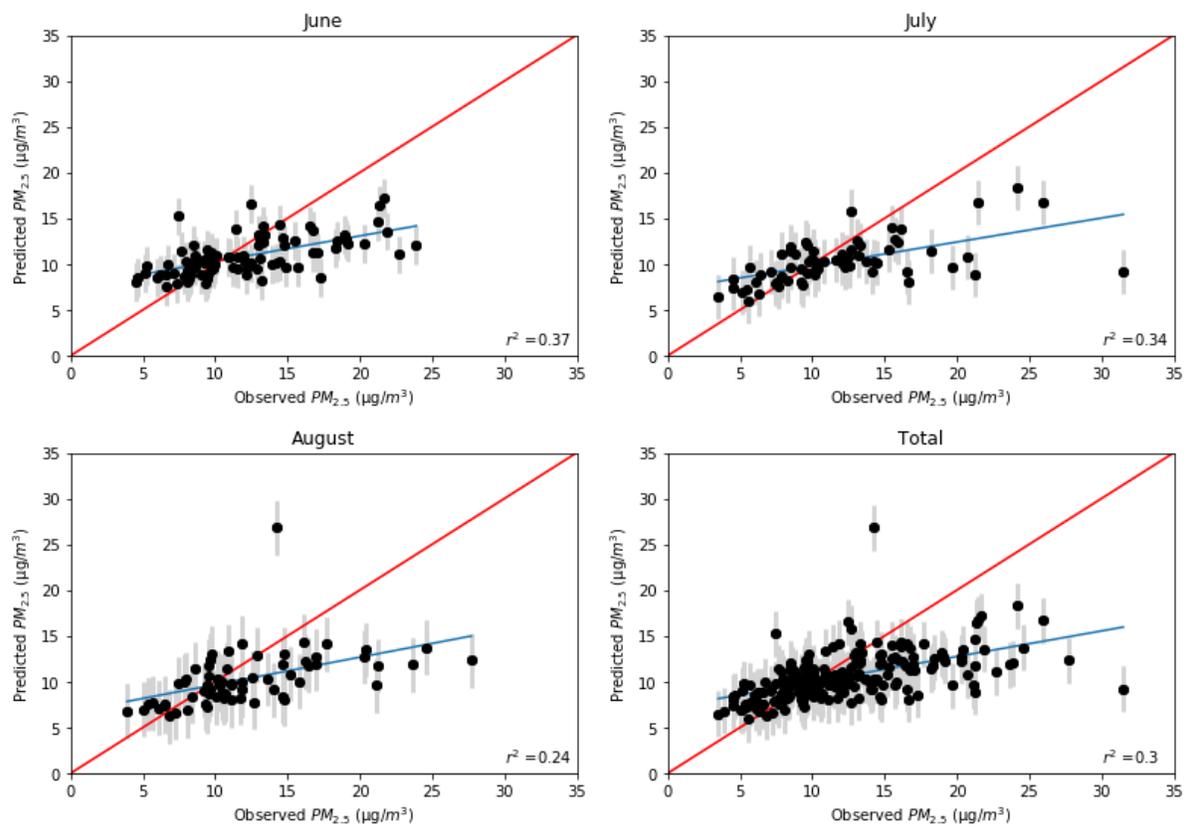


Figure 10. Scatter plots for Catawba county indicating model performance. The black points indicate the modeled versus predicted point, and the grey bars indicate the ± 1 standard deviation of the modeled dataset. The red line indicated the one to one line and the blue line is the best fit line for the data set.

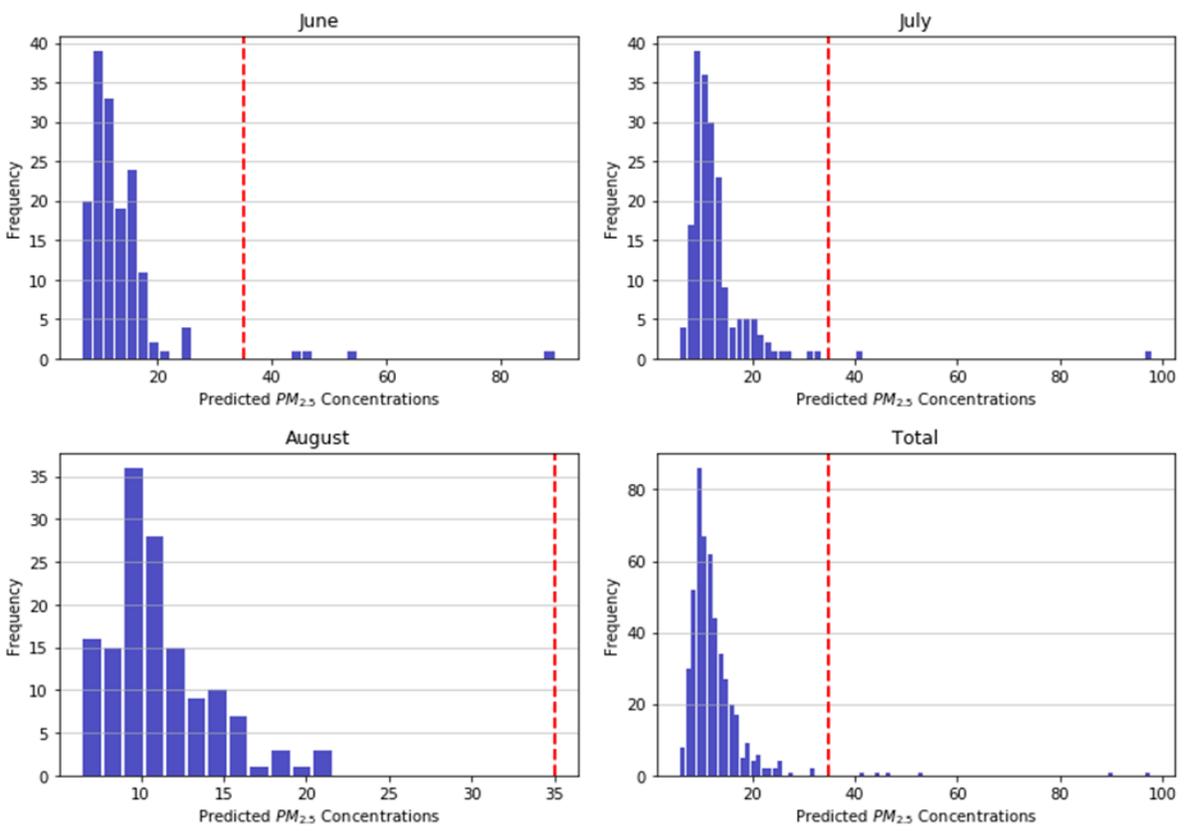
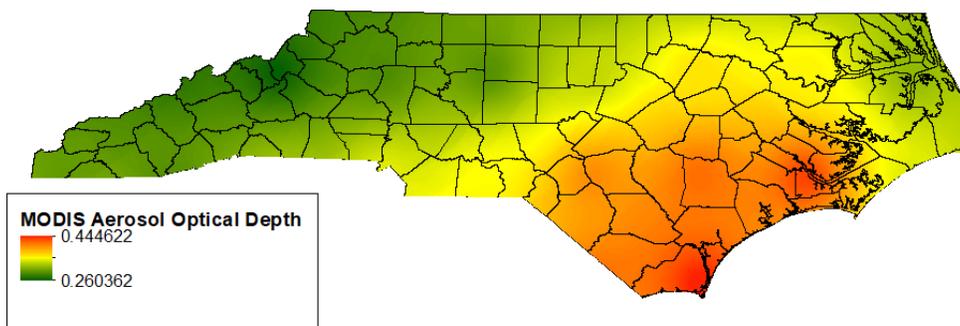
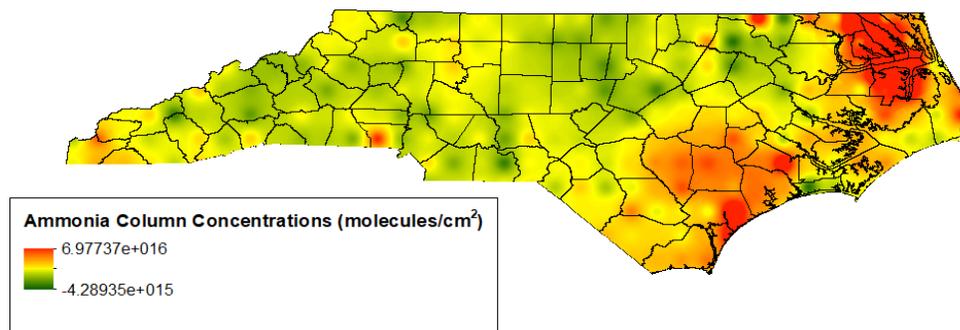


Figure 11. Histogram plot illustrating the model predictions in Sampson County. The red line indicates the PM_{2.5} NAAQS.

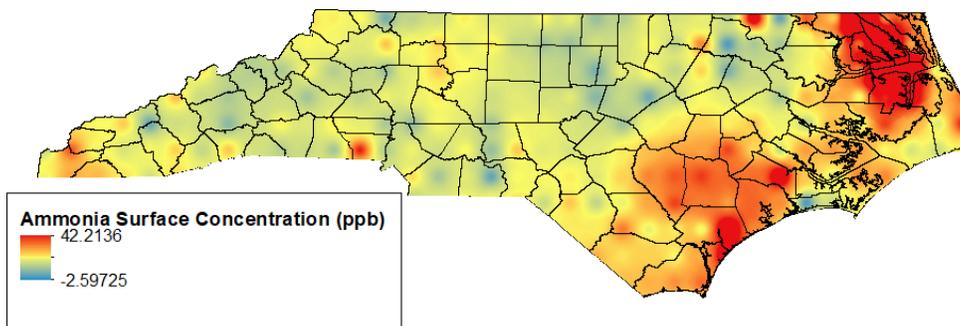
MODIS Aerosol Optical Depth for Summer 2011



IASI Column Ammonia Concentrations for Summer 2011



IASI Surface Ammonia Concentrations for Summer 2011



Ammonia Dry Deposition for Summer 2011

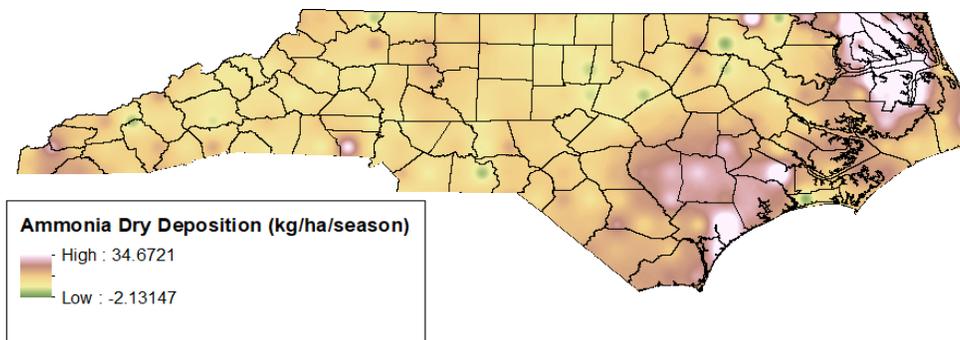


Figure 12: MODIS AOD for the summer of 2011, IASI column measurement for the summer of 2011, IASI surface measurements for summer 2011 and ammonia dry deposition for the summer of 2011.

APPENDICES

APPENDIX A: SAS

Statistical Analysis System (SAS) is a suite of analysis tools developed at North Carolina State University in the 1960s. It was developed to function as a way to deal with large groups of USDA agricultural data during that time. Now SAS is used for a variety of different statistical problems around the world from creating linear regression models to performing cluster analyzes on larger groups of data. For our purposes, SAS was used to create a multiple linear regression model to predict $PM_{2.5}$ using various other variables.

Using SAS version 9.4, the simple linear regression model procedure was used. The first step in running the procedure is to compile the data used to create the models. Cumberland County and Johnston County data was used to create a series of nine different models. Within the model there were six different variables that were used to predict the concentration of $PM_{2.5}$ in the area, ammonia retrievals from IASI, AOD retrievals from MODIS, temperature, pressure, wind speed and relative humidity from ground-based stations in Cumberland and Johnston county. Once the variables were decided upon, and averaged, they needed to be compiled in a way in which SAS could read. For this research the data was broken down by month, either June, July or August, and then by year. This was done for two reasons, one is related to how SAS understands and reads the data and the other is due to the type of models we were making. More about the models and the reasoning behind them can be seen in Appendix B. Finally, the data is normalized in SAS. Normalizing the data insure that the distribution of data gather for each month creates a data set that is easier for comparisons. Once SAS runs, it outputs the model along with a few other statistics to help explain the model's performance. These statistics explain the overall performance of the model along with the individual performance of each of the variables in the model, meaning the relative importance of the variables compared to the

overall model development and compared to the other variables in the model. It also looks at how much of the concentration's variance is explained by the variables used in the model.

APPENDIX B: Additional Models

Using SAS version 9.4, nine different models were created to predict $PM_{2.5}$ concentrations in four different locations. The nine different models encompassed three different locations, Cumberland County, Johnston County or the combination of Cumberland and Johnston Counties, and four different time periods, June, July, August or June July and August combined (referred to as summer). The reason for making nine models dependent on location and time frame was to capture the different meteorological and emission dynamic that would affect $PM_{2.5}$ concentrations throughout the months and in the different locations. Because the meteorology is different between the locations and during the three summer months, the models were designed to work for exclusively that month and that location or locations close by. This was designed in this way to see if creating different models for different months would create a stronger correlation value or if using all of the summer months together would create a better result to be used for all months.

The model performance can be seen in Table 6 along with its perspective temporal scale and the location it was built from. The table shows that other models had higher correlation values, for example the Cumberland County June model had the highest correlation value of 0.73, however through further testing of the model's performance, such as normalized mean bias, normalized mean error and general scatter plot trends, the Cumberland and Johnston County summer model performed better compared to the other models. This was the main reason in which this model was chosen and presented in this work over the other models. The other reason this model was chosen was to allow the model to be built with statistically more data points and more diverse data. Having more data built into the model would allow it to predict more

accurate concentrations and, in more location, which was one of the goals of the study, to be able to predict concentrations around the state and maybe into other states in the future.

Table 7: SAS model performance for all nine models.

	Cumberland County	Johnston County	Cumberland and Johnston Counties
June	0.73	0.68	-
July	0.43	0.72	-
August	0.39	0.42	-
Summer	0.41	0.48	0.43

APPENDIX C: Abstract and Presentation

2018 Environmental Health Scholars Program Fall Forum – Abstract and Poster

Fine Particulate Matter (PM_{2.5}) Pollution in Intensive Agricultural Region of North Carolina: Satellite Analysis and Integrate Ground-based Measurements

Rebecca D. Wiegand*, William H. Battye, Casey Bray, and Viney P. Aneja
Department of Marine, Earth, and Atmospheric Sciences
North Carolina State University, Raleigh, NC 27695-8208

***Corresponding Author:**

Email: rdwiegand@ncsu.edu

Abstract

Introduction

Intensive animal agriculture is an important part of North Carolina's economy. It produces ~ 10 million per year hogs, and ~190 million per year poultry primarily in the eastern part of NC. These farms produce large amounts of ammonia gas, which can lead to the formation of fine particulate matter (PM_{2.5}) around the state causing regional haze events along with human health effects such as respiratory illnesses and premature death. The objective of this research is to provide the relationship between ammonia from these agricultural farms and its effect on PM_{2.5} concentrations.

Methodology

Satellite derived ammonia and aerosol optical depth (AOD) values were used as a way to mitigate issues with the spatial distribution of ground-based measurement. A multiple linear regression model was derived to accurately predict ground level PM_{2.5} for a site in Cumberland County, North Carolina and Johnston County, North Carolina during the summer months (June, July and August) from 2008-2017. The model was created using the AOD retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASA's Aqua satellite along with surface PM_{2.5} monitor used by the Environmental Protection Agency and the North Carolina Department of Environmental Quality. The ammonia data used in the model was obtained through the Infrared Atmospheric Sounding Interferometer (IASI) located on board the MetOp-A satellite. The model also incorporated ground based metrological data as it has a significant impact on PM_{2.5} concentrations. The model was then utilized to predict PM_{2.5} concentrations in New Hanover County, Catawba County and Sampson county.

Results and Discussion

A combination of the Cumberland county model and the Johnston county model for the summer was chosen and validated for Duplin County, NC. The model is being used to predict Sampson County, NC concentrations. The model predicted a total of six 24-hour exceedances over the nine-year period.

For presentation at:
2018 Environmental Health Scholars Fall Forum
Duke University, Durham, NC
Friday, November 2, 2018.

Fine Particulate Matter (PM_{2.5}) Pollution in Intensive Agricultural Region of North Carolina: Satellite Analysis and Integrate Ground-based Measurements

Rebecca Wiegand* (rdwiegan@ncsu.edu), W. H. Battye, C. D. Bray and V. P. Aneja
 North Carolina State University, Raleigh, NC 27695-8208

Introduction

- North Carolina ranks in the top 10 states for hog and poultry production.
- These poultry and hog farms have been the subject of many lawsuits in the eastern portion of North Carolina during the past couple of months.
- Ammonia (NH₃) is a reactive form of nitrogen and is commonly released from these farms, specifically from the animal waste.
- Ammonia reacts very quickly within the atmosphere (lifetime of hours to a couple of days) and can form fine particulate matter, which has a negative impact on human health.
- Ammonia and particulate matter are normally measured through ground based measurements, however satellite data can be used for improved spatial resolution.

Objective: To create a multiple linear regression model to predict fine particulate matter (PM_{2.5}) based on remotely sensed variables and ground based meteorology data

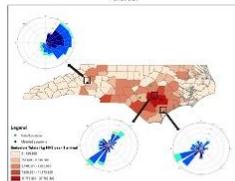


Figure 1. The initial locations that we built the model from are seen in blue while the locations we modeled can be seen in black. Animal density is indicated by the shading and the wind roses are used to indicate the predominate wind direction and speed from three sites, New Hanover, Sampson and Catawba counties in North Carolina.

Methods

Satellite Measurements

- Infrared Atmospheric Sounding Interferometer (IASI) ammonia concentrations where used from 2008-2017.
- Moderate Resolution Imaging Spectroradiometer (MODIS) Aerosol Optical Depth (AOD) data was used from 2008-2017.

Surface Measurements

- Ground-based meteorological data from the North Carolina State Climate Office was used at each location from 2008-2017.

Analysis

- A multiple linear regression model was built using ammonia concentrations, AOD data and ground based meteorological data to predict ground level PM_{2.5}.
- The model was built for Cumberland County and Johnston County, North Carolina during the summer months (June, July and August).
- It was then tested in Duplin County North Carolina, then used to predict concentrations in Catawba County, New Hanover County and Sampson County North Carolina.

MODIS Aerosol Optical Depth (0.55 μm) for July 30, 2011

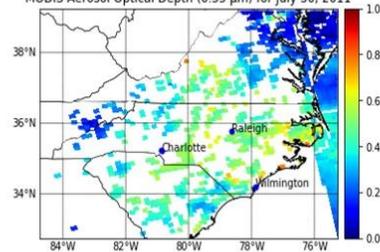


Figure 2. Aerosol Optical Depth (AOD) retrievals from the MODIS Aqua satellite for July 30th, 2011.

Results

Duplin County Results

- The model was tested for Duplin County due to its location near intense agricultural areas.
- Model showed promising result for Duplin County, producing a r² value of 0.36 and normalized mean bias (NMB) values ranging from 0.47% to 14.59% depending on the month.

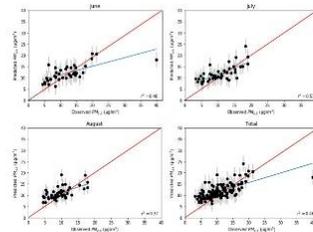


Figure 3. Scatter plots for Duplin county indicating model performance. The black points indicate the modeled versus predicted point, and the gray bars indicate the standard deviation of the modeled dataset. The red line indicated the one to one line and the blue line is the best fit line for the data set.

Catawba and New Hanover County Results

- The model was then tested for Catawba and New Hanover counties to test the limitations of the model.
- New Hanover county, located in eastern North Carolina, provided significant results, with an r² value of 0.29 and NMB values ranging from 17.62% to 19.82%.
- Catawba county, located near the mountains of North Carolina, provided slightly less promising results, with an r² value of 0.3 and NMB values ranging from -9.63% to -14.85%.

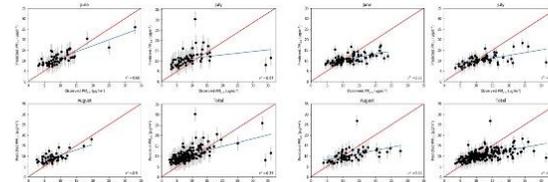


Figure 4a. Scatter plots for New Hanover county indicating model performance. The black points indicate the modeled versus predicted point, and the gray bars indicate the standard deviation of the modeled dataset. The red line indicated the one to one line and the blue line is the best fit line for the data set.

Figure 4b. Scatter plots for Catawba county indicating model performance. The black points indicate the modeled versus predicted point, and the gray bars indicate the standard deviation of the modeled dataset. The red line indicated the one to one line and the blue line is the best fit line for the data set.

Sampson County Results

- Finally, the model predicted concentrations in Sampson County which has the highest density of agricultural farms in the state.
- It has also never had a ground-based PM_{2.5} monitor.
- The model predicted 6 NAAQS exceedances over a nine year period.

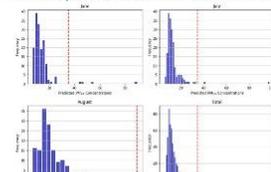


Figure 5. Histogram plot illustrating the model predictions in Sampson County. The red line indicates the NAAQS exceedance value.

Conclusions

- A multiple linear regression model was created using remotely sensed data and ground based meteorology data to predict PM_{2.5} concentrations in areas of high agricultural activity.
- The model indicated the potential to accurately predict these values in the eastern region of North Carolina.
- Using remotely sensed data is a viable option due to its increase spatial resolution compared to the ground based monitors.
- There is some correlation between high agricultural areas in the state and areas with higher PM_{2.5} concentrations, most likely due to the presence of ammonia in the atmosphere.
- In terms of control strategies, a reduction in ammonia emissions could result in a further reduction in PM_{2.5} emissions in high agricultural areas.



Figure 6. Ground-based PM_{2.5} monitor locations. These sites are set up and maintained by the Environmental Protection Agency (EPA) and the North Carolina Department of Environmental Quality (NCDEQ).

Limitations

- While the models showed good performance for the eastern North Carolina sites, its performance in western North Carolina was lacking.
- This is most likely due to elevation differences and different meteorological patterns that influence the western portion of the state.

Acknowledgements

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