ABSTRACT

LEWIS, BRANDON MAURICE. CAFO, Air Pollution, and Environmental Justice Modeling: The Case for North Carolina's Hog Industry. (Under the direction of Dr. Viney P. Aneja and Dr. William H. Battye).

Concentrated animal feeding operations (CAFOs) produces tons of animal waste, which can inherently pollute air, soil and water when not properly processed and filtered. The concentration of hog production in North Carolina have raised concerns of the disproportionate exposure of air pollution on vulnerable communities. Pollutants such as ammonia, hydrogen sulfide, acetaldehyde, and methanol are emitted by CAFOs and at high enough concentrations to affect human health. This research investigates the exposure of ammonia and hydrogen sulfide and possible health impacts of nearby community members looking at the disparities that may exist between different subpopulations. Characteristic data from 483 hog facilities within Duplin County including locations and hog inventory were gathered and processed for point source dispersion modeling. Emission factors from the U.S. Environmental Protection Agency in cooperation with Carnegie-Mellon University were used to calculate ammonia and hydrogen sulfide emission rates. We used the HEM-3 Human Exposure Model to estimate ambient concentrations of ammonia and hydrogen sulfide and the subsequent exposures on communities within Duplin County. We combine this with Census demographic data (2010) using spatial analysis to investigate whether exposures to these pollutants differ by race/ethnicity, age, income, education, and language proficiency. Based on these estimations, we assess associated health risks extenuating estimated concentrations. In this work, we limit our analysis to Duplin County, North Carolina. Results show that the average annual estimated concentration of ammonia in Duplin County is 6.05 μg/m3, and the average annual estimated concentration of hydrogen sulfide is 0.06 μg/m3. The maximum average annual ambient concentrations are

estimated at 51.67 μg/m3 and 0.52 μg/m3 for ammonia and hydrogen sulfide, respectively. Among vulnerable populations within Duplin County results show that people of low income, minorities, people with low educational attainment, and the linguistically isolated are disproportionately exposure to higher levels of ammonia and hydrogen sulfide on average. The linguistically isolated are estimated to experience 101% higher levels of exposure and people with low educational attainment more that 45% higher levels. Block group characterizations indicate a high prevalence of hogs and associated higher pollutant exposures in the two highest quintile compared with the lowest quintiles for each of these subpopulations. The partial distribution of ammonia and hydrogen sulfide exposures and hog facilities among communities may have adverse health effects and environmental impacts.

Confined Animal Feeding Operations (CAFO), Air Pollution, and Environmental Justice Modeling: The Case for North Carolina's Hog Industry

by
Brandon Maurice Lewis

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Marine, Earth, & Atmospheric Sciences

Raleigh, North Carolina

2020

APPROVED BY:

Dr. Viney P. Aneja Co-Chair of Advisory Committee	Dr. William H. Battye Co-Chair of Advisory Committee

Dr. Louie Rivers III

DEDICATION

This thesis is dedicated to everyone who encouraged and supported me throughout my journey at NC State. I count myself blessed to be able to complete this achievement and to continue forward. Without my faith in God and the strong support of the people who surrounded me and encourage me daily, I know that achievement would have been a heavier endeavor. I give my appreciation and gratitude to the family, friends, and mentors who have supported, loved, and guided me throughout my journey these past seven years. Thank you for being my village.

BIOGRAPHY

Brandon Maurice Lewis was born in Shelby, North Carolina on March 9, 1995 to Maurice Lewis and Kwanya Lewis. Growing up, Brandon's favorite activities were playing sports and enjoying music, including singing and playing the saxophone.   The inclination in music, lead to an affinity for the fine arts, but the passion in the sciences lead to the path to the path weather. This fascination started with the interest in the formation of clouds and grew from watching the abundance of documentaries on the history of severe weather and natural disasters. In 2013, Brandon graduated from Shelby High School with two distinct career path ahead as a meteorology or a music teacher. This path was made clear after completing his bachelor's degree in 2018 at North Carolina State University in Meteorology. Upon completion, Brandon pursued graduate school with his new found interest in air quality under the supervision of Dr. Viney Aneja at North Carolina State University. Within the Air Quality Research Group, Brandon worked closely with Dr. Aneja, Dr. William Battye, and Dr. Louie Rivers to develop and complete a research project that bridges his interest of air quality and environmental justice. After completion of his degree in 2020, Brandon hopes to continue his career and educational development within air quality and environmental justice.

ACKNOWLEDGMENTS

I would like to thank my committee members Dr. Viney P. Aneja, Dr. William H. Battye, and Dr. Louie Rivers III, for their time, support, and guidance in developing this thesis. I would like to thank Dr. Walter Robinson for his support during the duration of this research. I would also like to thank the members of the Air Quality Research Group, Dr. Pornpan “Lugwaa” Uttamang, Alberth Nahas, Ece Akdemir, Mike Pirhalla, and Dr. Casey Bray for their continuous encouragement and support as well. The North Carolina Department of Environmental Quality, United States Environmental Protection Agency, and the North Carolina State Climate Office were amazing resources throughout the duration of this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

CHAPTER 1. INTRODUCTION

1.1. Background

Over the past three decades, the rapid growth and restructuring of the swine industry in North Carolina has invigorated growing research within the movement on environmental and socioeconomic injustice. Environmental Justice (EJ) research addresses questions of who receives the most economic benefits from current policies, industrial development and establishment, environmental protection, and the disproportionality of resulting health consequences (Edwards and Ladd, 2001; Nicole, 2013). Today, threats of socioeconomic and environmental injustice due to the industrialization of agriculture and hog production aggravate these issues. Animal husbandry has gone through considerable transitions in these most recent decades in which small, privately owned animal operations has declined while the number of large, industrial operations have experienced growth (Edwards and Ladd, 2000), parallel to the consolidation of other commercial businesses like grocery and apparel stores. In North Carolina, this rapid transition initiated in the 1970s with Wendell Murphy and introduction of the contract hog farming and the application of the CAFO (Concentrated Animal Feeding Operations) model. This contract system allowed corporate entities to establish the exact environments by which swine is raised (Driscoll and Edwards, 2015). To meet demand for housing requirements, these corporate integrators promoted a CAFO production style with large animal populations. This CAFO model impacted hog production and eventually “pushed out” individual farmers. (Edwards and Ladd, 2000). Our focus of environmental justice is implicated within the transformation of the swine industry in North Carolina dominated by smaller independent hog farms to large, vertically integrated management of hog farms and the resulting disproportionate exposure of toxic air pollutants on neighboring communities composed of predominantly vulnerable populations.

In the mid-1980s to mid-1990s, North Carolina jumped from fifteenth to second leading state in swine production in the US with an estimated 10 million count greatly outweighing the state's human total of approximately 7.5 million according to the United States Department of Agriculture (USDA 2019; Wing et al., 2000). The expansion of swine production results in high volume of waste that is processed using waste management practices (Arogo et al., 2003; Aneja et al., 2008). This waste is channeled from hog houses to cesspools, called lagoons, where it is stored for anaerobic decomposition and then sprayed on land. Airborne emissions are released from confinement houses through the ventilation system and from lagoons and spray fields through volatilization. These pollutants emitted into the atmosphere include ammonia, hydrogen sulfide, methanol, acetaldehyde, other volatile organic compounds (VOCs), and particulate matter (Aneja et. al., 2000; Arogo et al., 2003; Rumsey et al., 2012; Cai et al., 2006). Ammonia (NH3) reacts with hydrochloric acid (HCl), sulfuric acid (H2SO4) and nitric acid (HNO3) to form secondary fine particulate matter (PM fine) as a mix of ammonium chloride, sulfate and nitrate salts. The process of gas-to-particle conversion (GTPC) of relatively short-lived gaseous ammonia to more persistent fine particles can affect local and regional air quality far away from the agricultural sources, and impact human health (Baek et. al., 2004). These pollutants can impact health leading to individual problems for those who are exposed. The contaminants have been associated with respiratory and cardiovascular ailments and premature mortality (Lelieveld et al., 2015; Lelieveld et al., 2019). Community members who are located near these industrial hog operations also report lower quality of life. A study in North Carolina provides evidence of effects of exposure of mood. These experiences include unpleasant odors, headaches and psychological effects such as tension, depression, anger, and fatigue (Schiffman et al., 1995; Avery et al., 2004; Horton et al., 2009). There are also economic concerns where these agricultural operations often remove a higher percentage of funds from rural communities unlike when this industry is dominated by privately owned operations (Donham et al., 2007).

1.2. History of Duplin County

The concentration of the pollution-intensive swine industry in the eastern section of North Carolina has become a prominent environmental justice issue (Driscoll and Edwards, 2015; Furuseth, 2004, Wing et al., 2000). North Carolina retains a high population of rural communities who are non-White and impoverished. The eastern half of North Carolina is located in the region originally named for the dark soils of the southeastern US but now its racial composition, the Black Belt. The Black Belt extends from Virginia, to the southern parts of Georgia, and to the eastern parts of Louisiana, Arkansas, and Tennessee. Historically, this region has been characterized by high rates of concentrated poverty and social isolation because of the large populations of disproportionately poor, uneducated, and politically incapacitated community members (Gibbs 2003; Austin et al., 2013). Thus, this area found a net of freed slaves residing in this area after the emancipation proclamation and a majority of black southern migrants returning to this region after World War 1 (Gibbs 2003).

The growth of the Hispanic population in North Carolina had its origins in the 1980s. This growth was largely due to the state's outlook for economic opportunity. The state experienced growth rates between 2010 and 2017 where about 30 of North Carolina's counties noted their Hispanic population increase by 25 percent of more (Alcalde 2012). This community also suffers high rates of concentrated poverty and social isolation known to this region. One NC county in particular, Duplin County is composed of around 50 percent White-alone, not Hispanic or Latino, and 50 percent minorities, showing above average populations of African Americans and Latino members. The United States comprises around 60 percent White-alone, not Hispanic or Latino, and 40 percent minorities, respectively (U.S. Census Bureau QuickFacts 2019). A notable 95% of hog farms are located in the eastern counties of the coastal plain of North Carolina (Driscoll and Edwards, 2015). A study in North Carolina has found that people of color including Blacks, Hispanics, and American Indians have higher chances of residing near CAFOs (Wing and Johnston, 2014). Another study has found that North Carolina communities located near hog CAFOs had higher all-cause and infant mortality rates (Kravchenko et al., 2018). This association and the lack of access to health care these communities face are not mutually exclusive. Principally, we observe people of color and the impoverished residing in rural communities having to bear the potential burden of dealing with socio-economic, environmental, or health related effects of swine waste superficies.

The location of emission sources amid disadvantaged populations may not necessarily be indicative of malevolent or discriminatory intent. Some studies suggest that agricultural industries or governments have simply followed "path of least resistance" in deciding areas where people were less likely to oppose or land was available for purchase at a low price (Mohai P, et al., 2009; Pulido L, 2000). Further economic explanations for the settling of these facilities also includes where farms labor pools and sources of materials are nearby. These sources can include access to water supply, access to feeds, and proximity to a slaughterhouse. Nevertheless, no matter the reason, we find our motivation in a circumstance that results in environmental injustice of vulnerable populations who are affected disproportionately.

Environmental justice is defined by the EPA as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies" (Environmental Justice, EPA, 2020). We identify environmental injustice as the disproportionate exposure and burden of pollution on vulnerable communities, including people of color and the poor. There have been few peer-reviewed studies that identify the racial and socioeconomic disparities relating to air pollution. Mikati et al. (2018) quantifies nationwide disparities from PM-emitting industries and found that disparities for Blacks are more pronounced than the basis or poverty status and even more so than Whites. Clark et al. (2017) estimated the changes of disparities of urban air pollution over time and found that relative NO2 exposures remained constant between 2000 to 2010, with higher concentrations for nonwhites than whites in 2010. Tessum et al. (2019) linked the disparities in pollution exposure and in consumption of goods and services in the United States. They found that PM2.5 (fine particulate matter) exposure is disproportionately caused by consumption of goods and services mainly by the non-Hispanic white majority, but disproportionately inhaled by black and Hispanic minorities. These studies document the need for further research on quantifying the effects and extent to which these exposures exist. There is a need for more research on disparities of air pollution exposure based on agricultural sources.

1.3. Previous Research

A few studies analyzed racial and socioeconomic disparities in the distribution of polluting industrial facilities by using surveying. Mohai et al. (2015) used individual-level survey data to provide records demonstrating significant disparities within the US populations. Wing et al. (2008) used community-based research to investigate the relationship between the resulting pollution and the health and quality by air quality and health monitoring and interviewing neighbors near hog operations. Other studies have used proximity analysis to link distance from

CAFOs to adverse health outcomes and disproportionate exposure of pollutants. Rasmussen et al. (2017) assessed associations of proximity to food animal production facilities in Pennsylvania and asthmatic exacerbations among asthma patients. Hooiveld et al. (2016) analyzed the associations between the presence of cattle, goat, poultry, and swine CAFOs and health of Dutch community residents. Schultz et al. (2019) examined the respiratory and allergic health of community members residing near dairy CAOFs in the Upper Midwest of the US. They found evidence that CAFOs can be a source of deteriorating air quality associated with health living in close proximity to a CAFO.

One limitation with proximity analysis is that it is an indirect measurement of air pollution exposure of industries nearby community members. Thus, distance is not directly associated with the pollutants inhaled from the source. Air pollution ambient concentrations which are directly inhaled, is a result of other proxies aside from proximity including, meteorology, surrounding topography and land use, facility inventory, facility housing and processing guidelines, facility waste management practices, and others. It is important to try to qualify the emissions released onto nearby communities to directly estimate the exposures and possible health risks. Similarly, Wilson and Serre (2007) measured weekly averaged ammonia levels near hog CAFO and communities with homes and schools in Eastern NC. They found evidence that distance to one or more CAFOs is a key variable in controlling weekly ammonia ambient concentration along with live animal weight per operation and found that indicators such as temperature, wind speed, and wind direction were important predictors of atmospheric ammonia at these locations.

1.4. Dispersion Modeling

Our study expands upon research conducted on the Contentnea Creek Watershed region in North Carolina in 2015 by Ogneva-Himmelberger et al. (2015). Ogneva-Himmelberger et al. (2015) used an air pollution dispersion model (CALPUFF) and CAFO data within the region to estimate ammonia concentrations, while we couple the HEM-3/AERMOD model in this study to estimate two pollutants ammonia and hydrogen sulfide. Bunton et al. (2007) assess the use of monitoring and modeling of emissions from CAFOs and note that accurate models are required to identify the spatial variability of concentrations over regions affected by CAFOs. From this an in-depth comprehension of the spatial and temporal variability of pollutant levels can then be used to determine the effect these concentrations have on the health of the resident living near the CAFOs. Models can be applied for research using dispersion on either a local or regional scale. Some studies have used dispersion modeling to apply to CAFOs and agricultural sources. RTI International (2003) used the Industrial Source Complex (ISC3) Dispersion Model (U.S. EPA, 1995) for modeling ammonia from swine CAFOs in eastern North Carolina. The Minnesota Pollution Control Agency used CALPUFF, a regional air quality computer model (U.S. EPA, 2005a), to estimate the potential air quality outcomes associated with the Hancock Project initiated to address the environmental and socioeconomic concerns from hog farrowing and nursery sites (Minnesota Pollution Control Agency, 2003).

Local scale dispersion modeling most often estimates concentrations in an area < 50km, and assesses ambient levels stemming from one or more sources. Previous research studies such as Thomas (2014) have used the air dispersion model, AERMOD, to estimate the dispersion of ammonia, hydrogen sulfide, and particulate matter from poultry buildings. The U.S. EPA recommended the Gaussian plume model, the American Meteorological Society/Environmental

Protection Agency Regulatory Model (AERMOD), for regulatory applications in November of 2005 which now AERMOD has become the U.S. EPA recommended model (U.S. EPA, 2005b). Becka et al. (2014) imposed AERMOD to assess the model's abilities to estimate SO2 emissions caused by industries in Muscatine, IA. Both of these studies were performed locally, similar to the use of AERMOD's capabilities in this study. An important assumption of this study is that facilities are running at maximum capacity at all times throughout the period of the modeling simulation. Thus, this will produce a conservative estimate of air pollution impacts Other limitations in this study includes the availability of activity and hog inventory data related to sales, not found from the hog farms themselves.

1.5. Motivation

In this study, we employ the Human Exposure Model (HEM-3) which couples census data with the AERMOD air pollution dispersion model to estimate ambient concentrations of ammonia and hydrogen sulfide due to CAFOs located within Duplin County, North Carolina. Our objective is to use an environmental justice framework to investigate exposures to residents located in and near Duplin county. Based on our assumption that exposures would differ by race/ethnicity, age, and socioeconomic indicators, we assemble block-group level census data and Duplin county hog inventory data and employ a geospatial analysis of the estimated pollutant levels. Using the capabilities of HEM-3 and implementing thresholds for hazardous air pollutants (HAPs), we estimate the health impact risks associated with our pollutant concentrations.

CHAPTER 2. MATERIALS AND METHODS

2.1. CAFO Definition and the Animal Feeding Operations Program

We acquired a 2019 list of the North Carolina and National Pollution Discharge Elimination System (NPDES)-permitted swine operations in North Carolina for the NC Department of Environmental Quality (NCDEQ) (North Carolina Environmental Management Commission, 2014; North Carolina Environmental Management Commission, 2017). The U.S. Environmental Protection Agency (U.S. EPA) Clean Water Act characterizes CAFOs as point sources that are required to be regulated under the NPDES permitting program (EPA, 1987). Furthermore, U.S. EPA identifies CAFOs as animal farming operations that meets one of three categories: (1) animal farming operations that produce manure and have greater than 1000 animal units (AUs) (large facilities), (2) facilities that discharge animal waste to waters or have a direct discharge to waters that pass through the facility come into direct contact with animals or, (3) contribute significantly to the impairment of the quality of a water body (USDA and US EPA, 1998). The Animal Feeding Operations Program is responsible for the permitting and compliance operations of animal feeding operations across North Carolina. Information detailing the farms that obtained permits were included in the 2019 list from NCDEQ. This information includes the permit name, facility name, facility location, the registered owner, the animal regulated and activity, the allowable count, number of lagoons, and location including the latitude/longitude coordinates.

2.2. Human Exposure Model and Environmental Justice Census Data

The Human Exposure Model, version 3 (HEM-3) is an air pollution exposure model that was implemented by the Environmental Protection Agency for performing risk assessments for sources emitting air toxics to ambient air. This model solely undertakes the inhalation track of exposure, and is intended to assess risks with respect to pollutants released into the ambient air. The HEM delivers ambient air concentrations, as proxies for lifetime exposure, for utilization with unit risk estimates and inhalation reference concentrations to construct estimates of cancer risk and non-cancer hazards, respectively, for the toxic chemicals modeled.

The HEM-3 couples air pollution dispersion model AERMOD, with pre-processed meteorological data, and U.S. Census Bureau data at the Census block level. In this study, we use 2010 Census data from the United State Census Bureau. Exposure estimates produced in HEM-3 are the ambient concentration predicted by AERMOD, in micrograms per cubic meter. These exposures predictions are integrated with pollutant health threshold values to estimate cancer risks and non-cancer hazards, cancer incidence, and other risk measures. The HEM-3 is unique because it calculates exposures based on the resulting concentration and uses this information to assess the predicted impact that these pollutants will have on human health (US EPA, HEM-3, 2019a).

The HEM-3 has 2 versions. A single-facility version (version 1.5), and a multi-facility version (version 1.55). We use the multi-facility version to model multiple CAFOs located in Duplin County. This multi-facility produces many files that summarize the combined results of all facilities included in the model (US EPA, 2019b).

We obtained specific census data from EPA’s Environmental Justice Screening Tool, EJSCREEN version 2018. EJSCREEN is a tool, developed by the EPA to meet the agency’s agenda and responsibilities for “protecting human health and the environment for all American” (US EPA, EJSCREEN, 2019). This tool combines demographic and environmental data in the form of environmental justice indexes. These are summaries of information as percentiles to compare with respect to location. The EJSCREEN dataset employs the 2016 (2012-2016)

American Community Summary Data, a 5-year summary census dataset from the U.S. Census Bureau (US CENSUS BUREAU, 2020). With this, we utilize the most recent data available in our analysis to represent the current populations in the U.S. This data is reported on the order of block groups and used coupled with HEM-3 to assess the risks by various demographic and socioeconomic groups.

We defined low-income as “poverty” according to the federally established poverty threshold in 1990. These thresholds are updated annually for inflation measured by the Consumer Price Index, and reported by the Department of Health and Human Services. The definition was developed by the social security administration (SSA) in 1964 and adopted by The Office of Management and Budget in the Statistical Policy Directive No. 14 (US Census Bureau, Subject Definitions, 2019). Linguistic isolation is defined by the U.S. Census as living in a household in which all members aged 14 years and older speak a non-English language and also speak English less than “very well” (US Census Bureau, 2000). We also used minority, as a non-white population, and low education attainment, have less than high school education. Along with these demographics, population size of the census block groups was also found.

2.3. Emissions Factors

Within modeling, a common approach to calculating pollutant emissions due to livestock is to multiply emission factor (with units such as kg per year per animal) by the number of animals with the specified set of facilities. This allows us to apply these emission factors to our agricultural facilities being modeled. Emission factors can vary greatly. From previous research, ammonia emission factors were found to be as low as 0.450 kg/yr/animal during the fall and high as 1.290 kg/yr/animal hydrogen and sulfide emission factors as low as 0.046 kg/yr/animal during the summer and higher as 0.160 kg/yr/animal during the winter, according to Bluden et al., 2008.

In the NEI 2014v2, VOC emissions were found in counties which provided an estimation of both pollutants in the 2014 version 1 National Emissions Inventory (NEI 2014v1). This ratio is multiplied by all county level ammonia emissions in NEI 2014 v2 to estimate VOC emissions for each county and the ratio does not vary by state or animal type. By this method, acetaldehyde was estimated to be as high as 13.80 g/year/ animal for the Duplin County region.

Ammonia emission factors used in our study were developed from a model implemented by Carnegie Mellon University and continued by the U.S. EPA (McQuilling and Adams, 2015). The model produced daily-resolved, climate referenced ammonia emission factors for a specific distribution of management practices for each U.S. county and animal type, identified as emissions/animal. The animal types included chicken broilers, chicken layers, swine, dairy cattle, and beef cattle. Within this model, the county level emission factors are totaled to create state level emission factors for each animal type. Within the National Emissions Inventory version 2 (NEI 2014v2) created by the U.S. EPA, these state level emissions factors were back-calculated from the CMU model using statewide emissions divided by statewide animal totals resulting in an ammonia emission factor of 12.76 kg/yr/animal. This is the average annual emission factor developed for the Duplin County Region.

Hydrogen sulfide factors used in our study are based on research by Rumsey and Aneja (2014). They determined hydrogen sulfide emission from a CAFO in North Carolina from measurement made during each of the four seasonal periods for one year. From this study, we calculated an emission factor of 0.127 kg/yr/animal. Rusmey et al. (2012) determined emission rates for non-methane VOCs from swine CAFOs in North Carolina. These measurements were made during the period of one year to include seasonal variability. This study reported normalized emissions rates for acetaldehyde and methanol as, 0.10 g/day/AU and 0.27

g/day/AU, respectively. For our purposes, we applied emission rates in units grams per year per animal (1 AU (animal unit) = 500 kg of live animal weight) resulting in 3.84 (g/yr/animal) and 10.37 (g/yr/animal).

2.4. Input Data Processing

HEM-3 requires three main sources of data inputs to files to run the Multi HEM-3 including: facility identifications, locations, and dimensions, upper air and surface meteorological data, and emissions data. HEM-3 includes a main component, AERMOD, to model the transportation of pollutants from emission sources and simulate transformation and dispersion throughout the period of the simulation. We modeled 483 facilities in our simulation. In addition, modeling so many facilities with specific dimensions and layout for each facility proves to be beyond the framework of our efforts in this study. Thus, we approximated each CAFO facility as a diffuse source with the dimensions configured at 100 meters squared, centered on their specified locations in the dataset provided by NCDEQ. These data inputs are formatted as data files within HEM-3.

We set the primary parameters and option within the HEM-3 model simulation in order to identify the hog facilities and model wet deposition and dry deposition of gaseous pollutants in the simulation. AERMOD allows for the input of user-specified parameters for dry deposition including diffusion coefficients, cuticular resistance, and Henry's Law coefficients. Gas parameters, shown in Table 1, are referenced from Theobald et al. (2012) who used these parameters to compare dispersion models to simulate agricultural ammonia emissions). HEM-3 and AERMOD is configured to perform a simulation for each identified CAFO where for every facility the ambient concentration and deposition impacts are estimate for all census blocks within 50km of the center of the hog facility. The modeling distance for each individual facility of ambient impacts for all census blocks was 3km where outside of this distance, ambient impacts are interpolated on a polar grid up to a distance of 50km. The ambient impacts from every single facility simulation were summed to produce the total cumulative impact of all CAFOs in Duplin county. We determined other additional settings within the capabilities of HEM-3 had no significant impacts to our results.

AERMOD requires surface and upper air meteorological data that meet specific format requirements. The meteorological surface and upper station that was to be used within AERMOD when modeling each facility was user-specified and represented the stations closest to the facility. The location of the selected surface station is located in Fayetteville, NC (34.99, 78.88 decimal degrees) and Greensboro, NC (36.08, 79.95 decimal degrees) for the selected upper air station both designated by the code, NC93740.SFC in AERMOD. These represent one National Weather Service (NWS) observation surface and upper air station in our model utilized for Duplin County. With this, we note the uncertainty introduced from the spatial availability of meteorological data and using only one meteorological station in our model to represent for Duplin County.

In this study, we model two pollutants: ammonia and hydrogen sulfide. The annual emissions for all sources were calculated using emission factors provided for Duplin County hogs by National Emissions Inventory and the total allowed hogs from NCDEQ permit data. For the facilities with multiple permits, we combined the total hogs permitted for that facility. Additionally, for each facility, we specified the latitude and longitude of the facilities, and the facility type as volume sources,1.8 meters, vertically, and 1-meter initial release height.

We included more additional modeling file options. We included the Land Use file and Month-to-Season Assignment file, both required to model dry deposition/depletion of gaseous pollutants. This land-use file listed the land use and vegetation surrounding each facility determined by the user. Given our input files and locations, the land type at each facility is unknown. The model domain is viewed as continuous forested land due to the rural characteristics of Duplin County. North Carolina experiences four seasons specified in a month-to-season file characterizing the stage of vegetation each month. December to February is identified as winter with snow on the ground. March to May is a transitional spring with partial green coverage. June to August is identified as autumn with unharvested cropland. Lastly, September to November is identified as late autumn after frost and harvest, or with no snow.

We modeled temporal variations in emissions by establishing emission factors based on different time scales such as season, month, day of the week, and hours of day or based on wind speed. We use the time scale of seasons (4) and hour-of day (24) for which both have significant effects on emission rates in our domain of Duplin County. This is primarily due to Duplin being located in the mid-latitudes, in the coastal plains of North Carolina were there strong diurnal and seasonal variations in temperature. This information was derived in the modeling framework for the 2016 National Emissions Inventory where temperatures data were collected and reported with emission rates for ammonia and factors created using a normal diurnal temperature profile. We applied a total of 96 emission rate factors for each facility to the emission rates in our model.

2.5. Reference Input Files

To calculate population risks and health hazards, HEM-3 includes a dataset of toxic unit risks estimates (UREs) and reference concentrations (RfCs). These risk factors and RfCs are established by the most recent values recommended by the EPA for hazardous air pollutants (HAPs) and other additional toxic air pollutants. In addition, the RfC for hydrogen sulfide was added to the library using values taken from EPA's Integrated Risk Information System (IRIS), also used for its other national modeling assessments. The Multi HEM-3 evaluates cancer risks and non-cancer “risks” (hazard indices) on the account of inhalation exposure at census block locations near the modeled sources. The estimated health risk predictions are generally underestimated with respect to the modeled emissions because they are not adjusted for diminishing exposure factors (e.g. outdoor/indoor concentration ratios, daily time spent away from the residential receptor location).

Non-cancer “risk” is estimated utilizing hazard quotients (HQs) and hazard indices for 14 “target” organs or systems unadjusted for diminishing exposure factors. These estimates return the risks of developing noncancerous ailments for an individual breathing the ambient air at a specific receptor site 24 hours per day over a 70-year lifetime. The HQ is the ratio of the ambient concentration of the chemical to the RfC at (and below) which no adverse health effects are expected. The chronic hazard index (HI) for a given target organ is the sum of HQs for pollutants that affect that organ. The pollutants in our study primarily target the respiratory system. The non-cancer RFCs are contained in the Dose Response reference file and the target organ endpoints impacted by various HAPs are included in the Target Organ Endpoints reference file.

2.6. RTR Summaries Program

HEM-3 allows for the summarizing of modeling multiple facilities combining the results of all the facilities using an add-on program, the Risk & Technology Review (RTR) summary programs. The RTR Summary Programs generates outputs that give the maximum cancer risk and the overall incidence with reference to emissions from all modeled facilities in the group. Results included estimated ambient concentrations and respiratory HI for all block groups and receptors modeled.

2.7. The Application of Graphic Information System (GIS)

We used ArcGIS to complete the analysis of our data. Data was imported into ArcMap 10.7.1 with corrected longitude and latitude. The results of HEM-3 and RTR Summary Programs, the EJSCREEN census data, and the location of the permitted operations were all displayed in ArcMap. All data was projected into the NAD 1983 State Plane North Carolina coordinate system. Census blocks within and adjacent to Duplin County, and CAFOs located within or near 3 miles of the Duplin County boundary were selected for the analysis. In summary, the dataset included 66 census blocks for 2010 and 483 permitted CAFOs. Figure 1 shows the spatial distribution of the permitted CAFOs in Duplin County and relative population of CAFOs in North Carolina.

Utilizing the census data, we totaled the number of youth (18-years and younger), the number of elderly (people aged 65 years or older), and the number of minority and white peoples. This demographic data is displayed in Table 2. In this study, we use the specific number of people within demographic groups, as it gives more relevance to our results of human exposure to air pollution in environmental justice analysis rather than percent per census block.

In our geographic analyses, we examined the distribution of the linguistically isolated, minorities, persons of low income, and persons of low education attainment (less that high school), respectively, in relation to the location of hog CAFOs in the County of Duplin. We depicted hog CAFOs and the environmental justice variables to exhibit their spatial relationships.

2.8. Analytical Methods

For each population demographic, with respect to the pollutants, we approximated the average exposure for one pollutant in Duplin County in its entirety by weighing each block group by the population using a method described by (Bell and Ebisu, 2012) whereas:

$$M_i = \frac{\sum_{j=1}^{J} D_{ij} w_j}{\sum_{j=1}^{J} D_{ij}}, \qquad [1]$$

Where M_i is the county average estimated exposure for any pollutant for persons who fall under the demographic i (e.g. linguistically isolated), j is the number of block groups with pollutant data (J = 173), $D_{i,j}$ is the number of persons under demographic i in block group j, and w is the concentration of pollutant of interest for census tract j. This gives an estimation of average exposure for a pollutant and population group, with respect to population size and pollutant levels in each block group.

We investigate the relationship between each environmental justice demographics and the exposure of pollutants from hog CAFOs by arranging block groups into quintiles of each environmental demographic and evaluating the average concentration level of estimated pollutants in the different tiers of the demographic variables. The ratio of the average concentration of a pollutant in each higher quintile compared with the lowest quintile is described as the prevalence ratio. A similar approach was used in a study of CAFO locations in Mississippi (Wilson et al., 2002). Continuing, the variables of 1) linguistically isolated and low education attainment and 2) minorities and low income were cross-classified in two-way tables. The distributions of the quintiles of these variables could not be defined together and their univariate associations were not linear. Thus, we assigned thresholds for the cross-classification that represented the higher and lower extents of prevalence, specified for each variable. The boundaries determined were: above or below 6% for linguistically isolated, above or below 25%

for linguistically isolated, above or below 44% for minorities, and above or below 25% for low income.

We used the results of RTR summaries program to estimate possible health risks for which the respiratory system is expected to be adversely affected from the exposure of all the pollutants modeled in our study. The total HI resulting from modeling Duplin CAFOs represent the total health risk contribution from agricultural sources. Whereas the emissions from non-agricultural sources can also contribute to the impact to respiratory health. Thus, we assess the total estimated respiratory HI for the Duplin County area by combining the agricultural sources and the non-agricultural sources where a total HI >1.0 indicates respiratory health concerns.

CHAPTER 3. RESULTS

3.1. Modeling for Duplin CAFOs

The spatial pattern of modeled ammonia concentrations is shown in Figure 2 and hydrogen sulfide in Figure 3. We used the inverse distance weighted interpolation method (IDW) to estimate the spatial coverage of our pollutant within the county from our modeled output given estimated at the receptors. Similarly, Li et al. (2016) used IDW as a method on a dataset of fine particulate matter (PM2.5) data to estimate population exposure in the U.S. Wong et al. (2004) found that different methods of interpolation do not produce considerable different estimations regarding the air pollutants estimated. The averaged estimated ammonia concentration within Duplin County is 6.05 μg/m3. The maximum modeled concentrations were approximately 51.67 μg/m3. The averaged estimated hydrogen sulfide concentration within Duplin County is 0.06 μg/m3. The maximum concentrations with modeled receptors within Duplin County was 0.52 μg/m3.

It is essential to recognize that emissions from our simulation is a result of only modeling swine CAFO sources and did not represent other sources of ammonia and hydrogen sulfide. The emissions released by poultry CAFOs represent a significant portion of total ammonia and other pollutants released by animal farming operations. Battye et al. (2003) estimated that 80% of ammonia emissions in North Carolina are accounted for by livestock wastes and other sources of contribution includes forests, vehicle emissions, fertilizer, and non-agricultural vegetation.

3.2. Choropleth Maps

Choropleth maps were used, shown in Figures 4-8, to display the spatial distribution of the ambient concentration of ammonia and hydrogen sulfide in relation to quintiles of percentage for each of our demographics of interest, linguistically isolated people, minorities, persons of low income, people with less than high school education, over the age 64, and under the age 5 for the entire county of Duplin.

These figures show the location of 483 swine farms throughout the entire Duplin region by which each red dot represents a swine farm with an active permit. The size of the pentagon represents the permitted inventory of each individual CAFO, shown in the legend. The color shading highlights the proportion of each vulnerable group specified within each block group. The map indicates that pork production generally occurs all over the county with the majority of the hog operations stationed in the northern portion of Duplin County. In addition, we note high numbers of people who have less than a high school degree, poor people, and minorities that are scattered throughout the region of the county, specifically in the western and northern section of Duplin County. We also note low numbers of children and elderly generally throughout the county.

However, in the southeastern portion of Duplin County we see block groups with relatively low numbers of minorities, people of low income, linguistically isolated, and people with low education attainment. We note higher numbers of linguistically isolated people located in the northern and southwestern portion of the county. There are high numbers of minorities along the western portion of the county. Located in these high linguistically isolated and minority areas are also large numbers of CAFO facilities and size of inventories indicated by the larger points.

Similarly, we note the distribution of low income in the county. About 26% of the persons in Duplin live below the poverty line (15,400 out of 58,600) (U.S. Census Bureau, 2019), this is higher than the national average of 13.1%. Most of the high-low income areas are located near the CAFOs with the larger inventory of hogs in the county. Majority high-low income areas are in census block groups located towards the western and northern part of the county. This is also true of the locations of the increasingly high proportions of people with less than high school education. Low income and low education attainment are not mutually exclusive.

The vulnerable populations characterized by age show no specific trends spatially within Duplin County shown in Figures 7 and 8. We show that there are low populations of elderly and children within Duplin County. It is worth noting, there are relatively higher numbers of children located in the northern portion of Duplin County than in the southern parts.

3.3. Weighted Averages Exposure

Figure 9 summarizes the percent differences in exposure by race, age, income, educational attainment, and language from the average population in Duplin County. All population categories and characteristic groups in this study, except the age group under 5, had higher exposures than the average population in Duplin County for each pollutant. Exposures in the context refers to the ambient concentration levels which these groups are exposed to. Exposures amid the linguistically isolated are higher than exposures among other vulnerable groups for each pollutant, respectively. The linguistically isolated group has exposure levels 101.0% higher than the average population. Relative differences in exposure are shown in Figure 4. The subpopulation of people with education less than high school degree had the second highest percent of exposure among the vulnerable subgroups with approximately 46% higher exposures on average. Children (under 5 years of age) have approximately 0.06% less exposures than the population and had the lowest estimated exposures for each pollutant. Older persons (over 64 years of age) had approximately 1.3% more exposures than the population. Both age groups show similar exposure levels compared to the general population in Duplin County.

Children and elderly are underrepresented in the Duplin population and are estimated to have exposures comparable to the average citizen within the county, thus we limit our discussion of the exposure of the elderly and children for the purposes of our study. It should be recognized that these two populations should still be recognized as vulnerable populations in future studies.

3.4. Data of Prevalence

Table 3 displays the distribution of ambient concentrations of ammonia and hydrogen sulfide in Duplin County in relation to proportions of the linguistically isolated. Within the lowest quintile for proportion of linguistically isolated, there are 25 block groups that contain no people from this subpopulation. We also see that the lowest quintile for the group contains on average the lowest concentrations of both ammonia and hydrogen sulfide at 3.56 μg/m3 and 0.018 μg/m3, respectively. Conversely, highest concentrations on average are seen in the highest two quintiles of percentage of the linguistically isolated.

Table 4 displays data on the characteristics of census block groups for the percentage of minorities. There are 75 hog farms in the lowest quintile of percentage of minorities while the average ammonia and hydrogen concentrations are 3.58 μg/m3 and 0.019 μg/m3, respectively. The second lowest quintile of percentage of minorities contains average concentrations of 3.67 μg/m3 and 0.018 μg/m3. Conversely, the highest quintile of this subpopulation contains the highest number of CAFOs at 113 facilities. The highest two quintiles of percentage of minorities (55.58-99.66%) contain the highest average concentrations of ammonia (5.69 μg/m3 and 5.39 μg/m3) and hydrogen sulfide (0.028 μg/m3 and 0.027 μg/m3).

Similar analyses are shown in Tables 5 and 6 presenting the proportions of persons with low income and persons with low educational attainment. The lowest quintile of percentage of persons with low income contains the lowest number of CAFOs, 71 and the lowest average concentration of ammonia and hydrogen sulfide of 3.60 μg/m3 and 0.018 μg/m3, respectively. The highest quintile of percentage of persons with low income contains the higher number of CAFO, 135 and the highest average concentration of ammonia and hydrogen sulfide of 5.48 μg/m3 and 0.027 μg/me, respectively. This pattern is also seen in the subpopulation of persons who have less than a high school education. We note that in the lowest quintile for the percentage of persons with low educational attainment, there are 62 hog CAFOs compared with 125 CAFOs in the highest quintile. We also note that the highest quintile of percentages of persons with low educational attainment has the highest average concentrations of ammonia and hydrogen sulfide of this subgroup, at 6.15 μg/m3 and 0.031 μg/m3.

3.5. Prevalence Ratios

Using four of our demographic groups of interest, we examined cross-divisional combinations of minorities and people of low income, and of the linguistically isolated and people with less than high school education equivalency for the county of Duplin. Table 7 displays the prevalence ratios of hog farms for minorities and people of low income cross-division. The table shows the ambient ammonia concentration (in μg/m3) for the categories and the ratio of prevalence of hog CAFOs at each level compared with the lowest or reference level. For this table, 0-45% low income and 0-44% minorities are the reference group. High-minority, low-poverty block groups experience 1.4 times more exposure than the reference group. The high-minority, high-poverty block groups suffer 1.7 times more exposure than the reference group.

Table 8 presents prevalence ratios for the linguistically isolated and people with less than high school education cross-division for Duplin County. Altogether, block groups in the 0-25% less than high school educated and 0-6% linguistically isolated represents the reference group.

The high-less than high school educated and low-linguistically isolated block groups experience 1.14 times more exposure than the reference group while the high-less than high school educated and high-linguistically isolated block groups are 1.4 times more exposed to ammonia and hydrogen sulfide.

3.6. Health Risk

Maximum hazard indices (HI) for non-cancer chronic health effects and the hazard quotient (HQ) are reported for each census block group. In our study, only the impact of the respiratory system was considered based on the effects of our modeled pollutants as noted. We did not report a RfC value for ammonia in our model, thus ammonia was not incorporated into the resulting respiratory HI risks estimated. We reported an RfC value of .002 mg/m3 for hydrogen sulfide (U.S. EPA IRIS, 2003). We report a maximum respiratory HI of 0.064 for Duplin County. We determine a HQ of 0.063 solely from hydrogen sulfide and report that hydrogen sulfide accounts for about 99% of the non-cancer risks modeled. The EPA reported RfC value of 0.5 mg/m3 for ammonia within the IRIS Assessments (U.S. EPA IRIS, 2016). From this value, a HQ of 0.103 is estimated.

Our maximum estimated respiratory HI represents the non-cancer risks stemming from hog farms in Duplin County. Hog farms represent a significant proportion of the agricultural sources contributing to the exposure impact on respiratory health. It is noted that 0.064 is the total agricultural contribution to respiratory HI at the block group level. There are non-agricultural sources that are characterized by EPA’s 2014 National Air Toxics Assessment (U.S. EPA NATA, 2018). The reported total non-agricultural respiratory HI or (HQ) for this region is approximately 0.39 at the track level for Duplin County. Agricultural contributions represent

14% of the total contribution to respiratory HI (agricultural HI sources + non-agricultural sources).

CHAPTER 4. DISCUSSION

Our goal for this study was to evaluate ambient impacts from air pollutants emitted from hog CAFOs in Duplin County, North Carolina, and to determine whether minority populations, or other disadvantaged populations are disproportionately exposed these to impacts. Of concern are air pollutants ammonia, hydrogen sulfide, and HAPs emitted from hog CAFOs in Duplin County, North Carolina. To address this question, the study evaluated emissions of ammonia, hydrogen sulfide, and HAPs from these facilities, and then used the HEM-3 model to estimate ambient impacts from these facilities. We then used Census data to examine the differentiation of pollutant exposure within vulnerable populations in Duplin County's communities.

The HEM-3 model utilizes the AERMOD dispersion model using detailed meteorological conditions and the characteristics of CAFO facilities, including ammonia and hydrogen sulfide emissions, CAFO locations, and inventory of hogs to produce ambient concentration measurements. The HEM-3 estimates exposures spatially at the census block group and census tract-level which allows for the overlaying and coupling of exposures with census data. We analyzed the locations of 483 facilitated hog operations with respect to vulnerable populations within census block groups in and adjacent to Duplin County, North Carolina.

The average annual estimated ammonia concentration within Duplin County is 6.05 μg/m3 with the maximum annual concentration estimated at a receptor at 51.67 μg/m3. The average annual estimated hydrogen sulfide concentration within Duplin County is 0.06 μg/m3 with the maximum annual concentration estimated at a receptor at 0.52 μg/m3. There are no monitoring stations near Duplin County that currently measure ammonia, hydrogen sulfide, or HAPs. The North Carolina Department of Environment and Natural Resources (now NC Department of Environmental Quality (NCDEQ)) collected ammonia measurements in Clinton, North Carolina within Sampson County, halting operations in 2015 (NCDEQ 2016; Shendrikar et al., 2016)). Clinton monitoring station observed an annual average ambient concentration of 2.6 μg/m3 in 2015 and 4.6 μg/m3 in 2004. Assessing a 10-year monthly average of the Clinton measurements, the highest concentrations during the month of June were 5.2 μg/m3 for the 2004 to 2015 period. Our modeled ammonia concentration estimates agree with observational values by a factor of 3. It should be noted that Sampson County is located adjacent to Duplin County and thus does not represent Duplin emissions, but because of Clinton's proximity, in this study we use these observations as a proxy for comparison.

Using geospatial analysis, we introduce an environmental justice aspect by examining how exposures of ammonia and hydrogen sulfide may differ by population for minorities, the linguistically isolated, people of low income, and people with low educational attainment.

We found that the majority of Duplin CAFOs are located in areas with higher proportions of minorities and linguistically isolated. We also found that the majority of larger CAFOs are found more in communities of low income. Over half of all hogs are located in block groups with more than 55% minorities, while less than 45% of Duplin CAFOs are located in these same block groups. This provides evidence that industrialized industries are located disproportionately closer to non-white and low-income communities supported by previous studies (Wing and Johnston, 2014; Kravchenko et al., 2018; Mohai et al., 2009; Wilson et al., 2007; Wilson et al., 2002).

4.1 Exposures

Our estimates are consistent with overall trends indicating that the highest pollutant exposures occur in minority communities and those in with low-income (Tessum et al., 2019; Mikati et al., 2018; Clark et al., 2017; Ogneva-Himmelberger et al., 2015; Bell and Ebisu, 2012).

We see above average exposures of ammonia and hydrogen sulfide for linguistically isolated communities, minorities, communities of low income and of low educational attainment. The overall differences were sizable with the largest difference given at 101% higher for linguistically isolated communities than for the average exposure in Duplin County. We also assess large differences in exposures among people of low educational attainment at 46% higher and minorities at 23% higher. We examine smaller differences in magnitude, with exposures at 18% higher for low income communities.

We computed local exposures for block groups extending to census tracts. It would be beneficial to employ spatial heterogeneity for more accurate measurements (Peng and Bell 2010), additionally, exposures from on job-sites, indoor exposures (e.g. stoves, fireplaces, environmental tobacco smoke), daily activity patterns, and individual or average inhalation rates. Most of these factors can differ between populations. In this study, factors are included in the hazard indices for non-cancer risks which reflect possible health risk given from the ambient concentration emissions from our model. We should note because our estimates are on the block group level and census tract level, they do not reflect the personal exposures of individuals with Duplin county.

In this study, we do not analyze the interrelationships among the demographic characteristics of race/ethnicity, education, unemployment, poverty, and earnings. Bell and Ebisu (2012) shows how race, education, earnings, and poverty were correlated in their examination of population characteristics in relation to PM2.5. To this point, we examined the joint effects of race and income along with linguistically isolation and education. In Duplin County, there are approximately 1.7 times higher levels of ammonia and hydrogen sulfide concentrations in high minority, high low income block groups compared with the referent group. Furthermore, in high linguistically isolated, high-low educational attainment block groups there are about 1.43 times higher levels of ammonia and hydrogen sulfide concentrations than the referent group. Future work could examine patterns in other demographic characteristics in relation to ammonia and hydrogen sulfide.

In our model, we assumed hog facilities to be at full capacity in accordance with their permits throughout the model simulation. In actuality, the farms may operate below their capacity. In addition, as inventories change temporarily during the year, and we note that it is difficult to model the temporal emissions from a single facility for 483 individual facilities. Further, we have simplified the spatial representation of the facilities. Modeling scenarios could be improved/modified for future analysis. This also includes taking into account the type of facility (finishing verses breeder facility). Secondly, collecting more data on the management practices such as the control of ammonia and other gases in facilities that use waste amendments and technologies. Third, additional more detailed meteorological data would allow for characterizing the local atmospheric conditions in Duplin county.

Our methodology is based on that used in the National Air Toxics Assessment which reports results as the Census block level. Results at the block level are more uncertain, since we have not gathered detailed information on the physical layouts of CAFOs, and on the actual proximity of neighboring residential neighborhoods. Instead, the Census block group data used in this analysis gives only the general average location of populations within a block. (A Census block typically represents an average location for about 50 people.) Future studies should assess similar methodologies to conduct the analysis at smaller geographic scales. Assessing the impacts of biological contamination of hog waste should also be taken into consideration as studies such as Pisanic et al. (2015) and Heaney et al. (2015) have looked at hog farms as microbial and pathogenic sources.

Additional studies, such as this based on pollution dispersion modeling and finer scale population data, will allow for others to evaluate the inequitable distribution of CAFOs operations and exposure to potentially toxic airborne pollutants and odors of these industrialized farming industries in heavily impacted areas such as Duplin County. There is a collective awareness and need to address concerns regarding public health and environmental impact from the aggregation of CAFOs and environmental equity issues resulting from the disproportionality of CAFOs in vulnerable communities.

CHAPTER 5. CONCLUSION

Our findings suggest differences in exposure of ammonia and hydrogen sulfide among and between populations in Duplin County. The disproportionate distribution of hog CAFOs among these populations could contribute to these findings. We estimated the health risks associated with our estimated exposures although, exposure difference and the estimated health risks may only partly determine whether health impacts are more prevalent between populations. The difference in associated health impacts also depend on how these effects are reshaped by population characteristics. In this study, we suggest that some populations experience higher exposures than others, and that health responses with these populations should be considered based on our given disproportionate exposures. Lastly, the economic stability and vitality of these communities within Duplin county should also be taken into consideration on account of the disproportionate number of CAFOs among these populations.

Our study contributes to a larger reservoir of literature on environmental justice and the employment of risk assessment within this issue. In this study, we incorporate two gases, i.e. ammonia and hydrogen sulfide, within our exposure model and estimate the impact on six vulnerable populations; including educational attainment and language as a barrier contributing to vulnerability. Few studies have recognized these as vulnerable groups, and they are seldom included in environmental justice research. Few studies have also used dispersion modeling and ambient concentrations as a proxy for environmental justice assessment.

This study emphasized the need for more research to understand the role of dispersion modeling in understanding the spatial and temporal resolution of pollutants when discussing uneven exposure among communities. These findings also highlight the need for understanding risk assessment with reference to multiple pollutants released by these animal operations.

Throughout, we note the complexity of our research given by the deficient data on these industries, pollutant emissions, and limitations within our model. Nonetheless, this work provides insight into the disproportionate exposures of air pollutants from CAFOs in Duplin County, and can be used to motivate and inform future research.

In addition to this future work, it is necessary to discuss effects resulting from the ongoing COVID-19 outbreak and possible implications that this may have on people affected by agricultural industries. Hendryx and Luo (2020) have found that areas with poorer air quality may be at greater COVID-19 risk and resulting fatalities. Cole et al. (2020) also have shown evidence that poor air quality and increases in $PM_{2.5}$ ambient concentrations are associated with more COVID cases, hospital admissions and fatalities. Lovarelli et al. (2020) surmised that agricultural activities like livestock production have not slowed down and thus associated pollution emitted, such as NH_3, has shown no reductions even though NO_x and $PM_{2.5}$ emissions have seen a reduction during the quarantine period. Animal feeding operations emit NH_3, a precursor to $PM_{2.5}$, H_2S, and other VOCs. Essential workers in these slaughterhouses could be more vulnerable to COVID-19 due underlying conditions such as exposure to prior pollutants. This will effect community members living near these farms as well. Continuing, the linguistically isolated represent a large proportion of these essential workers. As we continue addressing concerns regarding disparities in health impacts from air pollution and COVID-19, there is also now a need to address the disproportionate susceptibility to COVID-19 of vulnerable populations like essential workers and communities residing near animal operations and other agricultural activities.

REFERENCES

Alcalde, M. C. (2012). The Latino Migration Experience in North Carolina: New Roots in the Old North State by Hannah Gill. *The Latin Americanist*, *56*(2), 189–191. https://doi.org/10.1111/j.1557-203x.2012.01155_6.x

Aneja, V. P., Arya, S. P., Kim, D. S., Rumsey, I. C., Arkinson, H. L., Semunegus, H., . . . Williams, C. M. (2008). Characterizing Ammonia Emissions from Swine Farms in Eastern North Carolina: Part 1—Conventional Lagoon and Spray Technology for Waste Treatment. *Journal of the Air & Waste Management Association, 58*(9), 1130-1144. doi:10.3155/1047-3289.58.9.1130

Aneja, V.P., J.P. Chauhan, and J.T. Walker, 2000, “Characterization of Ammonia Emissions from Swine Waste Storage and Treatment Lagoons,” Journal of Geophysical Research-Atmospheres, Vol. 105, pp. 11535-11545.

Animal Feeding Operations (AFOs). (2020, July 29). US EPA. https://www.epa.gov/npdes/animal-feeding-operations-afos#regs

Austin, S. D., Franklin, S. M., & Lewis, A. K. (2013). The Effects of Concentrated Poverty on Black and White Political Participation in the Southern Black Belt. *The National Political Science Review*, 57–69. http://bsc.chadwyck.com/search/displayIibpCitation.do?SearchEngine=Opentext&fromPage=fulltext&area=iibp&QueryName=iibp&id=00463004&journalID=0896629X

Avery, R. C., Wing, S., Marshall, S. W., & Schiffman, S. S. (2004). Odor from Industrial Hog Farming Operations and Mucosal Immune Function in Neighbors. *Archives of Environmental Health: An International Journal*, *59*(2), 101–108. https://doi.org/10.3200/aeoh.59.2.101-108

Baek, B.H., V.P. Aneja, and Quansong Tong, 2004, “Chemical coupling between ammonia, acid gases, and fine particles”, Environmental Pollution, vol. 129, pp. 89-98.

Battye, W., Aneja, V.P. and Rolelle, P. (2003). Evaluation and improvement of ammonia emissions inventories. *Atmospheric Environment*, *37*(27), 3873–3883. https://doi.org/10.1016/s1352-2310(03)00343-1

Battye, W. H., Bray, C. D., Aneja, V. P., Tong, D., Lee, P., & Tang, Y. (2019). Evaluating Ammonia (NH 3) Predictions in the NOAA NAQFC for Eastern North Carolina Using Ground Level and Satellite Measurements. *Journal of Geophysical Research: Atmospheres*, *124*(14), 8242–8259. https://doi.org/10.1029/2018jd029990

Becka, C. M., O’Shaughnessy, P., Spak, S., & Cwiertny, D. (2014). A case study of sulfur dioxide concentrations in Muscatine, Iowa and the ability for AERMOD to predict NAAQS violations. *University of Iowa*, 1. https://doi.org/10.17077/etd.ypvpzzz8

Bell, M. L., & Ebisu, K. (2012). Environmental Inequality in Exposures to Airborne Particulate Matter Components in the United States. *Environmental Health Perspectives*, *120*(12), 1699–1704. https://doi.org/10.1289/ehp.1205201

Blunden, J., Aneja, V. P., & Westerman, P. W. (2008). Measurement and analysis of ammonia and hydrogen sulfide emissions from a mechanically ventilated swine confinement building in North Carolina. *Atmospheric Environment*, *42*(14), 3315–3331. https://doi.org/10.1016/j.atmosenv.2007.06.040

Bunton, B., O'Shaughnessy, P., Fitzsimmons, S., Gering, J., Hoff, S., Lyngbye, M., Thorne, P. S., Wasson, J., & Werner, M. (2007). Monitoring and Modeling of Emissions from Concentrated Animal Feeding Operations: Overview of Methods. *Environmental Health Perspectives*, *115*(2), 303–307. https://doi.org/10.1289/ehp.8838

Cai, L., Koziel, J. A., Lo, Y.-C., & Hoff, S. J. (2006). Characterization of volatile organic compounds and odorants associated with swine barn particulate matter using solid-phase microextraction and gas chromatography–mass spectrometry–olfactometry. *Journal of Chromatography A*, *1102*(1–2), 60–72. https://doi.org/10.1016/j.chroma.2005.10.040

Clark, L. P., Millet, D. B., & Marshall, J. D. (2017). Changes in Transportation-Related Air Pollution Exposures by Race-Ethnicity and Socioeconomic Status: Outdoor Nitrogen Dioxide in the United States in 2000 and 2010. *Environmental Health Perspectives*, *125*(9), 097012. https://doi.org/10.1289/ehp959

Cole, Matthew A., Ozgen, C. & Strobl, E. (2020), Air Pollution Exposure and COVID-19. IZA Discussion Paper No. 13367, Available at SSRN: https://ssrn.com/abstract=3628242

Donham, K. J., Wing, S., Osterberg, D., Flora, J. L., Hodne, C., Thu, K. M., & Thorne, P. S. (2007). Community Health and Socioeconomic Issues Surrounding Concentrated Animal Feeding Operations. *Environmental Health Perspectives*, *115*(2), 317–320. https://doi.org/10.1289/ehp.8836

Driscoll, A., & Edwards, B. (2015). From Farms to Factories: The Social and Environmental Consequences of Industrial Swine Production in North Carolina. *From Farms to Factories: The Social and Environmental Consequences of Industrial Swine Production in North Carolina*, 1. https://www.researchgate.net/publication/326020122_From_Farms_to_Factories_The_Social_and_Environmental_Consequences_of_Industrial_Swine_Production_in_North_Carolina

Edwards, B., & Ladd, A. E. (2000). ENVIRONMENTAL JUSTICE, SWINE PRODUCTION AND FARM LOSS IN NORTH CAROLINA. *Sociological Spectrum*, *20*(3), 263–290. https://doi.org/10.1080/027321700405054

Edwards, B., & Ladd, A. E. (2001). Race, poverty, political capacity and the spatial distribution of swine waste in North Carolina, 1982-1997. *The North Carolina Geographer*, *9*, 51–70.

https://www.academia.edu/1446269/Race_poverty_political_capacity_and_the_spatial_distribution_of_swine_waste_in_North_Carolina_1982-1997?auto=download

Environmental Justice. (2020, July 10). US EPA. https://www.epa.gov/environmentaljustice

EPA. (1987). *Clean Water Act* (Section 502). https://www.epa.gov/cwa-404/clean-water-act-section-502-general-definitions#:~:text=(1)%20The%20term%20%22State,to%20the%20abatement%20of%20pollution.

Faulkner, W. B., & Shaw, B. W. (2008). Review of ammonia emission factors for United States animal agriculture. *Atmospheric Environment*, *42*(27), 6567–6574. https://doi.org/10.1016/j.atmosenv.2008.04.021

Furuseth, O. J. (2004). Restructuring of Hog Farming in North Carolina: Explosion and Implosion. *The Professional Geographer*, *49*(4), 391–403. https://doi.org/10.1111/0033-0124.00086

Gibbs, R. M. (2003). Reconsidering the southern black belt. *The Review of Regional Studies, 33(3)*, 254–263. https://proxying.lib.ncsu.edu/index.php/login?url=https://search.proquest.com/docview/1691272274?accountid=12725

Heaney, C. D., Myers, K., Wing, S., Hall, D., Baron, D., & Stewart, J. R. (2015). Source tracking swine fecal waste in surface water proximal to swine concentrated animal feeding operations. *Science of The Total Environment*, *511*, 676–683. https://doi.org/10.1016/j.scitotenv.2014.12.062

Hendryx, M., & Luo, J. (2020). COVID-19 prevalence and fatality rates in association with air pollution emission concentrations and emission sources. *Environmental Pollution*, *265*, 115126. doi:10.1016/j.envpol.2020.115126

Hooiveld, M., Smit, L. A. M., van der Sman-de Beer, F., Wouters, I. M., van Dijk, C. E., Spreeuwenberg, P., Heederik, D. J. J., & Yzermans, C. J. (2016). Doctor-diagnosed health problems in a region with a high density of concentrated animal feeding operations: a cross-sectional study. *Environmental Health*, *15*(1), n/a. https://doi.org/10.1186/s12940-016-0123-2

Horton, R. A., Wing, S., Marshall, S. W., & Brownley, K. A. (2009). Malodor as a Trigger of Stress and Negative Mood in Neighbors of Industrial Hog Operations. *American Journal of Public Health*, *99*(S3), S610–S615. https://doi.org/10.2105/ajph.2008.148924

J. Arogo, P. W. Westerman, & A. J. Heber. (2003). A REVIEW OF AMMONIA EMISSIONS FROM CONFINED SWINE FEEDING OPERATIONS. *Transactions of the ASAE*, *46*(3), 41–88. https://doi.org/10.13031/2013.13597

Kravchenko, J., Rhew, S. H., Akushevich, I., Agarwal, P., & Lyerly, H. K. (2018). Mortality and Health Outcomes in North Carolina Communities Located in Close Proximity to Hog Concentrated Animal Feeding Operations. *North Carolina Medical Journal*, *79*(5), 278–288. https://doi.org/10.18043/ncm.79.5.278

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., & Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, *525*(7569), 367–371. https://doi.org/10.1038/nature15371

Lelieveld, J., Klingmüller, K., Pozzer, A., Pöschl, U., Fnais, M., Daiber, A., & Münzel, T. (2019). Cardiovascular disease burden from ambient air pollution in Europe reassessed using novel hazard ratio functions. *European Heart Journal*, *40*(20), 1590–1596. https://doi.org/10.1093/eurheartj/ehz135

Li, L., Zhou, X., Kalo, M., & Piltner, R. (2016). Spatiotemporal Interpolation Methods for the Application of Estimating Population Exposure to Fine Particulate Matter in the Contiguous U.S. and a Real-Time Web Application. *International Journal of Environmental Research and Public Health*, *13*(8), 749. https://doi.org/10.3390/ijerph13080749

Lovarelli, D., Conti, C., Finzi, A., Bacenetti, J., & Guarino, M. (2020). Describing the trend of ammonia, particulate matter and nitrogen oxides: The role of livestock activities in northern Italy during Covid-19 quarantine. *Environmental Research, 191*, 110048. doi:10.1016/j.envres.2020.110048

McQuilling, A. M., & Adams, P. J. (2015). Semi-empirical process-based models for ammonia emissions from beef, swine, and poultry operations in the United States. *Atmospheric Environment*, *120*, 127–136. https://doi.org/10.1016/j.atmosenv.2015.08.084

Mikati, I., Benson, A. F., Luben, T. J., Sacks, J. D., & Richmond-Bryant, J. (2018). Disparities in Distribution of Particulate Matter Emission Sources by Race and Poverty Status. *American Journal of Public Health*, *108*(4), 480–485. https://doi.org/10.2105/ajph.2017.304297

Minnesota Pollution Control Agency. (2003). *Draft Environmental Impact Statement on the Hancock Pro Pork Feedlot Project, Stevens and Pope Counties*. https://www.pca.state.mn.us/sites/default/files/hancock-eis.pdf

Mohai, P., Lantz, P. M., Morenoff, J., House, J. S., & Mero, R. P. (2009). Racial and Socioeconomic Disparities in Residential Proximity to Polluting Industrial Facilities: Evidence From the Americans' Changing Lives Study. *American Journal of Public Health*, *99*(S3), S649–S656. https://doi.org/10.2105/ajph.2007.131383

Mohai, P., Pellow, D., & Roberts, J. T. (2009). Environmental Justice. *Annual Review of Environment and Resources*, 405–430. https://doi.org/10.1146/annurev-environ-082508-094348

NCDEQ. (2016). *Latest Ambient Monitoring Data*. Ambient Data Site. https://xapps.ncdenr.org/aq/ambient/AmbtSiteEnvista.jsp

Ni, J.-Q., Heber, A. J., Cortus, E. L., Lim, T.-T., Bogan, B. W., Grant, R. H., & Boehm, M. T. (2012). Assessment of ammonia emissions from swine facilities in the U.S.—Application of knowledge from experimental research. *Environmental Science & Policy*, *22*, 25–35. https://doi.org/10.1016/j.envsci.2012.06.001

Nicole, W. (2013). CAFOs and Environmental Justice: The Case of North Carolina. *Environmental Health Perspectives*, *121*(6), 182–189. https://doi.org/10.1289/ehp.121-a182

North Carolina Environmental Management Commission. (2014, October). *Swine Waste Management System General Permit* (No. AWG100000). https://files.nc.gov/ncdeq/Water%20Quality/Aquifer%20Protection/AFO/Permits/AWG100000%20Signed%203-7-2014.pdf

North Carolina Environmental Management Commission. (2017, July). *Swine Waste Management System NPDES General Permit* (No. NCA200000). https://files.nc.gov/ncdeq/Swine%20NPDES%20General%20Permit%2012-5-2016.pdf

Ogneva-Himmelberger, Y., Huang, L., & Xin, H. (2015). CALPUFF and CAFOs: Air Pollution Modeling and Environmental Justice Analysis in the North Carolina Hog Industry. *ISPRS International Journal of Geo-Information*, *4*(1), 150–171. https://doi.org/10.3390/ijgi4010150

O'Shaughnessy, P. T., & Altmaier, R. (2011). Use of AERMOD to determine a hydrogen sulfide emission factor for swine operations by inverse modeling. *Atmospheric Environment*, *45*(27), 4617–4625. https://doi.org/10.1016/j.atmosenv.2011.05.061

Peng, R. D., & Bell, M. L. (2010). Spatial misalignment in time series studies of air pollution and health data. *Biostatistics*, *11*(4), 720–740. https://doi.org/10.1093/biostatistics/kxq017

Pisanic, N., Nadimpalli, M., Rinsky, J. L., Stewart, J., Wing, S., Love, D. C., Hall, D., & Heaney, C. D. (2015). Pig-2-Bac as a biomarker of occupational exposure to pigs and livestock-associated Staphylococcus aureus among industrial hog operation workers. *Environmental Research*, *143*, 93–97. https://doi.org/10.1016/j.envres.2015.09.026

Pulido, L. (2000). Rethinking Environmental Racism: White Privilege and Urban Development in Southern California. *Annals of the Association of American Geographers*, *90*(1), 12–40. https://doi.org/10.1111/0004-5608.00182

Rasmussen, S., Casey, J., Bandeen-Roche, K., & Schwartz, B. (2017). Proximity to Industrial Food Animal Production and Asthma Exacerbations in Pennsylvania, 2005–2012. *International Journal of Environmental Research and Public Health*, *14*(4), 362. https://doi.org/10.3390/ijerph14040362

RTI International, Cajka, J., Deerhake, M., & Yao, C. (2003). *Modeling Ammonia Dispersion from Multiple CAFOs Using GIS*. https://proceedings.esri.com/library/userconf/proc04/docs/pap1381.pdf

Rumsey, I. C., Aneja, V. P., & Lonneman, W. A. (2012). Characterizing non-methane volatile organic compounds emissions from a swine concentrated animal feeding operation. *Atmospheric Environment*, *47*, 348–357. https://doi.org/10.1016/j.atmosenv.2011.10.055

Rumsey, I. C., Aneja, V. P., & Lonneman, W. A. (2014). Characterizing reduced sulfur compounds emissions from a swine concentrated animal feeding operation. *Atmospheric Environment*, *94*, 458–466. https://doi.org/10.1016/j.atmosenv.2014.05.041

Schiffman, S. S., Sattely Miller, E. A., Suggs, M. S., & Graham, B. G. (1995). The effect of environmental odors emanating from commercial swine operations on the mood of nearby residents. *Brain Research Bulletin*, *37*(4), 369–375. https://doi.org/10.1016/0361-9230(95)00015-1

Schultz, A. A., Peppard, P., Gangnon, R. E., & Malecki, K. M. C. (2019). Residential proximity to concentrated animal feeding operations and allergic and respiratory disease. *Environment International*, *130*, 104911. https://doi.org/10.1016/j.envint.2019.104911

Shendrikar, A. D., Steger, J., Kimball, H., Cornelius, W., Yirka, M., Bishop, R., & Joyner, N. (2016). *ATMOSPHERIC AMMONIA MONITORING AROUND HOG FARM INDUSTRIES IN NORTH CAROLINA*. https://files.nc.gov/ncdeq/Air%20Quality/monitor/specialstudies/NH3_monitoring_around_hog_farms.pdf

Tessum, C. W., Apte, J. S., Goodkind, A. L., Muller, N. Z., Mullins, K. A., Paolella, D. A., Polasky, S., Springer, N. P., Thakrar, S. K., Marshall, J. D., & Hill, J. D. (2019). Inequity in consumption of goods and services adds to racial–ethnic disparities in air pollution exposure. *Proceedings of the National Academy of Sciences*, *116*(13), 6001–6006. https://doi.org/10.1073/pnas.1818859116

Theobald, M. R., Løfstrøm, P., Walker, J., Andersen, H. V., Pedersen, P., Vallejo, A., & Sutton, M. A. (2012). An intercomparison of models used to simulate the short-range atmospheric dispersion of agricultural ammonia emissions. *Environmental Modelling & Software*, *37*, 90–102. https://doi.org/10.1016/j.envsoft.2012.03.005

Thomas, D. Y. (2014). *Estimating the dispersion of pollutants from poultry buildings using AERMOD (AERMOD, air modeling, particulate matter, poultry, ammonia, dispersion modeling)*. https://proxying.lib.ncsu.edu/index.php/login?url=https://search.proquest.com/docview/1770365216?accountid=12725

United States Department of Agriculture. (2019). *USDA/NASS QuickStats Ad-hoc Query Tool*. National Agricultural Statistics Service. https://quickstats.nass.usda.gov/results/E0B7DDAB-00F5-3AB2-903C-FED0F4A7A3F2

US Census Bureau. (2019, August 7). *Subject Definitions*. The United States Census Bureau. https://www.census.gov/programs-surveys/cps/technical-documentation/subject-definitions.html

US Census Bureau. (2020, April 16). *American Community Survey Summary File Data*. The United States Census Bureau. https://www.census.gov/programs-surveys/acs/data/summary-file.2016.html

U.S. Census Bureau QuickFacts: United States; Duplin County, North Carolina. (2019). Census Bureau QuickFacts. https://www.census.gov/quickfacts/fact/table/US,duplincountynorthcarolina/PST045219

U.S. Census Bureau, Seigel, P., Martin, E., & Bruno, R. (2000, November). *Language Use and Linguistic Isolation: Historical Data and Methodological Issues*. https://www.census.gov/hhes/socdemo/language/data/census/li-final.pdf

U.S. ENVIRONMENTAL PROTECTION AGENCY. (1995, September). *USER'S GUIDE FOR THE INDUSTRIAL SOURCE COMPLEX (ISC3) DISPERSION MODELS*. https://www3.epa.gov/scram001/userg/regmod/isc3v2.pdf

U.S. Environmental Protection Agency. (2003). *Hydrogen sulfide; IRIS* (No. 7783-06–4). https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0061_summary.pdf#nameddest=rfc

U.S. Environmental Protection Agency. (2005a). *Adoption of a Preferred General Purpose (Flat and Complex Terrain) Dispersion Model and Other Revisions*. https://www3.epa.gov/ttn/scram/guidance/guide/appw_05.pdf

U.S. Environmental Protection Agency. (2005b, November). *Guideline on Air Quality Models*. https://www.federalregister.gov/documents/2005/11/09/05-21627/revision-to-the-guideline-on-air-quality-models-adoption-of-a-preferred-general-purpose-flat-and

U.S. Environmental Protection Agency. (2016, September). *Ammonia: IRIS*. https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0061_summary.pdf#nameddest=rfc

U.S. Environmental Protection Agency. (2018, August). *Technical Support Document EPA's 2014 National Air Toxics Assessment (NATA)*. https://www.epa.gov/sites/production/files/2018-09/documents/2014_nata_technical_support_document.pdf

U.S. Environmental Protection Agency. (2019a, January). *The HEM-3 User's Guide*. https://www.epa.gov/sites/production/files/2017-06/documents/hem_users_guide.pdf

U.S. Environmental Protection Agency. (2019b, April). *Multi HEM-3 and RTR Summary Programs User's Guide*. https://www.epa.gov/sites/production/files/2017-06/documents/multi_hem-3_users_guide.pdf

U.S. Environmental Protection Agency (EPA). (2019). *EJSCREEN Technical Documentation*. https://www.epa.gov/sites/production/files/2017-09/documents/2017_ejscreen_technical_document.pdf

USDA & US EPA. (1998, September). *Unified National AFO Strategy Executive Summary*. https://www.epa.gov/sites/production/files/2015-10/documents/exexsum.pdf

Wilson, S. M., Howell, F., Wing, S., & Sobsey, M. (2002). Environmental injustice and the Mississippi hog industry. *Environmental Health Perspectives, 110*(suppl 2), 195–201. https://doi.org/10.1289/ehp.02110s2195

Wilson, S. M., & Serre, M. L. (2007). Examination of atmospheric ammonia levels near hog CAFOs, homes, and schools in Eastern North Carolina. *Atmospheric Environment, 41*(23), 4977–4987. https://doi.org/10.1016/j.atmosenv.2006.12.055

Wing, S. (2002). Social responsibility and research ethics in community-driven studies of industrialized hog production. *Environmental Health Perspectives*, *110*(5), 437–444. https://doi.org/10.1289/ehp.02110437

Wing, S., Cole, D., & Grant, G. (2000). Environmental injustice in North Carolina's hog industry. *Environmental Health Perspectives*, *108*(3), 225–231. https://doi.org/10.1289/ehp.00108225

Wing, S., Horton, R. A., Muhammad, N., Grant, G. R., Tajik, M., & Thu, K. (2008). Integrating Epidemiology, Education, and Organizing for Environmental Justice: Community Health Effects of Industrial Hog Operations. *American Journal of Public Health*, *98*(8), 1390–1397. https://doi.org/10.2105/ajph.2007.110486

Wing, S., & Johnston, J. (2014). *Industrial Hog Operations in North Carolina Disproportionately Impact African-Americans, Hispanics and American Indians*. http://www.ncpolicywatch.com/wp-content/uploads/2014/09/UNC-Report.pdf

Wong, D. W., Yuan, L., & Perlin, S. A. (2004). Comparison of spatial interpolation methods for the estimation of air quality data. *Journal of Exposure Science & Environmental Epidemiology*, *14*(5), 404–415. https://doi.org/10.1038/sj.jea.7500338

Wood, D., Cowherd, S., & Van Heyst, B. (2015). A summary of ammonia emission factors and quality criteria for commercial poultry production in North America. *Atmospheric Environment*, *115*, 236–245. https://doi.org/10.1016/j.atmosenv.2015.05.069

Table 1. Summary of gas parameters used within the dispersion modeling frame (AERMOD) of HEM-3. These gas parameters were taken from Theobald et al. (2012) who used these to estimate ammonia emission within in AERMOD and other dispersion models. We used these parameters for both ammonia and hydrogen sulfide for Duplin County.

Gas Parameters	**Value**
Diffusion Coefficient in Air ($cm^2\ sec^{-1}$)	1.98E-01
Diffusion Coefficient in Water ($cm^2\ sec^{-1}$)	1.64E-05
Cuticular Resistance ($sec\ cm^{-1}$)	6.00E+00
Henry's Law Coefficient ($Pa\ m^3\ mol^{-1}$)	1.62E+00

Table 2. Demographic populations of interest within Duplin County. Six subgroups within the total populations of Duplin represents some of the vulnerable populations within the county. These populations represent the populations that tend to be vulnerable to and more effected by environmental concerns due to their age, income, education level, race/ethnicity, or language capacities.

Duplin County Demographic Characteristics (2010)	Population Total
Total Population	108128
Minorities	48309
Linguistically Isolated	2190
Low Income	55093
Less Than HS Education	18999
Under Age 64	16009
Over Age 5	6834

Table 3. A summary of the characters of block groups with respect to the linguistically isolated within Duplin County. Block groups are separated into five quintiles with respect to the subgroup. Within each quintile, summaries of approximated number of hogs, number of CAFOs, and estimated annually average ammonia and hydrogen sulfide concentrations are given.

Environmental Justice Variable	Quintiles/ Percentages	Total population	Average Concentration of NH_3 ($\mu g\ m^{-3}$)	Average Concentration of H_2S ($\mu g\ m^{-3}$)	Number of Allowable Hogs	Number of Block Groups	Number of CAFOs
Percentage	0	39563	3.56	0.036	625000	25	149
of	0.01-4.58	13323	4.74	0.048	195000	10	47
Linguistically	4.59-7.05	17501	4.45	0.044	264000	9	71
Isolated	7.06-12.65	13653	5.66	0.056	460000	9	87
	12.66-25.58	17857	5.28	0.052	480000	10	85

Table 4. A summary of the characters of block groups with respect to the minorities within Duplin County. Block groups are separated into five quintiles with respect to the subgroup. Within each quintile, summaries of approximated number of hogs, number of CAFOs, and estimated annually average ammonia and hydrogen sulfide concentrations are given.

Environmental Justice Variable	Quintiles/ Percentages	Total population	Average Concentration of NH_3 ($\mu g\ m^{-3}$)	Average Concentration of H_2S ($\mu g\ m^{-3}$)	Number of Allowable Hogs	Number of Block Groups	Number of CAFOs
Percentage of Minorities	2.76-25.35	19629	3.58	0.038	274000	12	75
	25.36-35.72	21325	3.67	0.036	434000	13	103
	35.73-55.57	21470	4.40	0.044	368000	13	86
	55.58-63.92	22771	5.69	0.056	515000	13	102
	63.93-99.66	19124	5.39	0.054	639000	13	113

Table 5. A summary of the characters of block groups with respect to the linguistically isolated within Duplin County. Block groups are separated into five quintiles with respect to the subgroup. Within each quintile, summaries of approximated number of hogs, number of CAFOs, and estimated annually average ammonia and hydrogen sulfide concentrations are given.

Environmental Justice Variable	Quintiles/ Percentages	Total population	Average Concentration of NH_3 ($\mu g\ m^{-3}$)	Average Concentration of H_2S ($\mu g\ m^{-3}$)	Number of Allowable Hogs	Number of Block Groups	Number of CAFOs
Percentage	19.94-41.45	23506	3.60	0.036	287000	14	71
of Persons	41.46-48.77	18784	3.95	0.040	275000	13	71
with Low	48.78-54.06	20770	4.18	0.042	394000	13	102
Income	54.07-62.32	22335	5.38	0.054	611000	13	104
	62.9-77.38	22733	5.48	0.054	674000	13	135

Table 6. A summary of the characters of block groups with respect to people with less than a high school education within Duplin County. Block groups are separated into five quintiles with respect to the subgroup. Within each quintile, summaries of approximated number of hogs, number of CAFOs, and estimated annually average ammonia and hydrogen sulfide concentrations are given.

Environmental Justice Variable	Quintiles/ Percentages	Total population	Average Concentration of NH_3 ($\mu g\ m^{-3}$)	Average Concentration of H_2S ($\mu g\ m^{-3}$)	Number of Allowable Hogs	Number of Block Groups	Number of CAFOs
Percentage Less Than High School Education	1.42-16.88	22037	3.95	0.040	282000	14	62
	16.89-22.29	21245	3.72	0.036	309000	13	75
	22.30-27.06	19114	3.98	0.040	398000	13	102
	27.07-35.34	19981	4.76	0.048	584000	13	119
	35.35-59.19	25751	6.15	0.062	669000	13	125

Table 7. A summary of the prevalence ratios of the exposures of ammonia and hydrogen sulfide per block group for block groups with respect to the percentage of minorities and percentage of people of low income within Duplin County.

	Minority (%)	
Low Income (%)	0-44	44-100
0-45	1.00 (3.20)	1.40 (4.48)
45-100	1.19 (3.81)	1.70 (5.45)

Table 8. A summary of the prevalence ratios of the exposures of ammonia and hydrogen sulfide per block group for block groups with respect to the percentage of linguistically isolated and percentage of people with an education level below high school within Duplin County.

	Linguistically Isolated (%)	
Less Than High School (%)	0-6	6-100
0-25	1.00 (3.90)	1.05 (4.11)
25-100	1.14 (4.46)	1.43 (5.56)

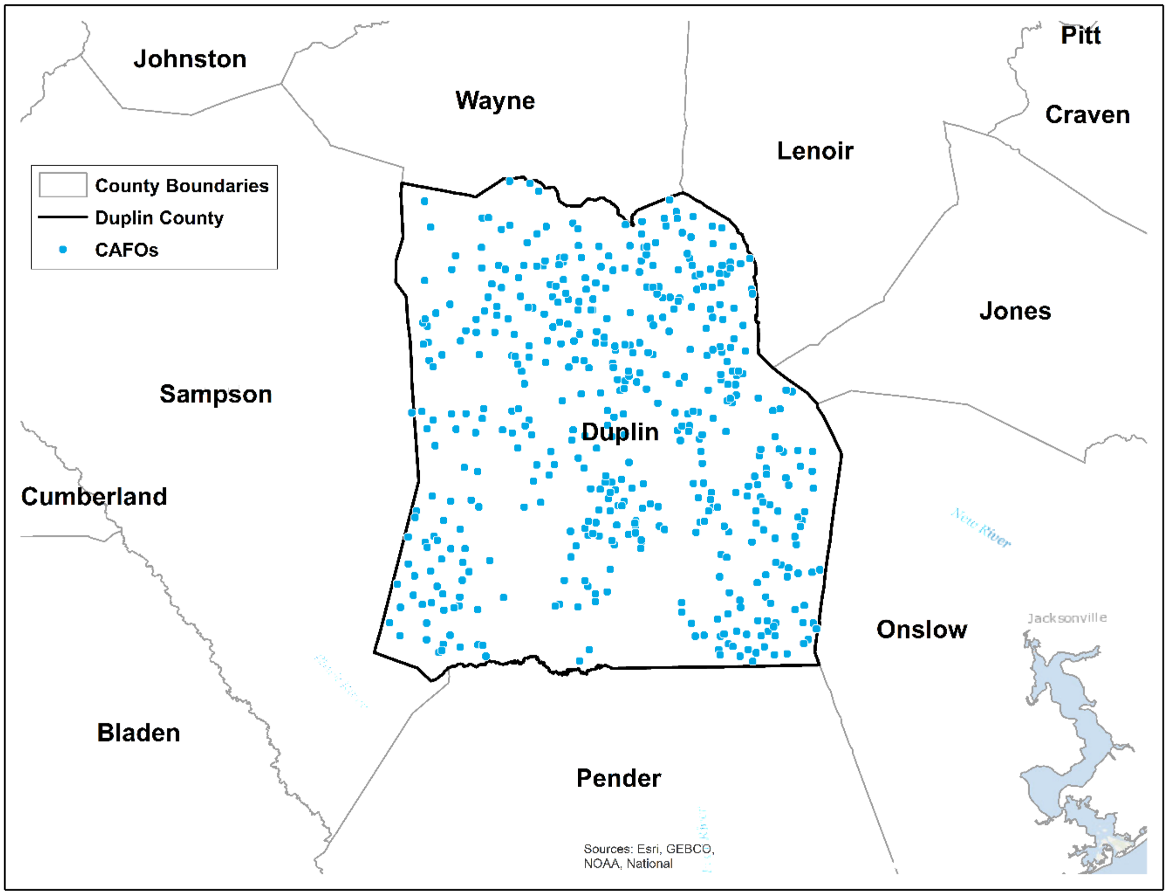

Figure 1. Spatial distribution of hog CAFOs within Duplin County along with the surrounding counties adjacent to Duplin County, NC. Map represents all of the permitted CAFOs as accounted for by the North Carolina Department of Environmental Quality.

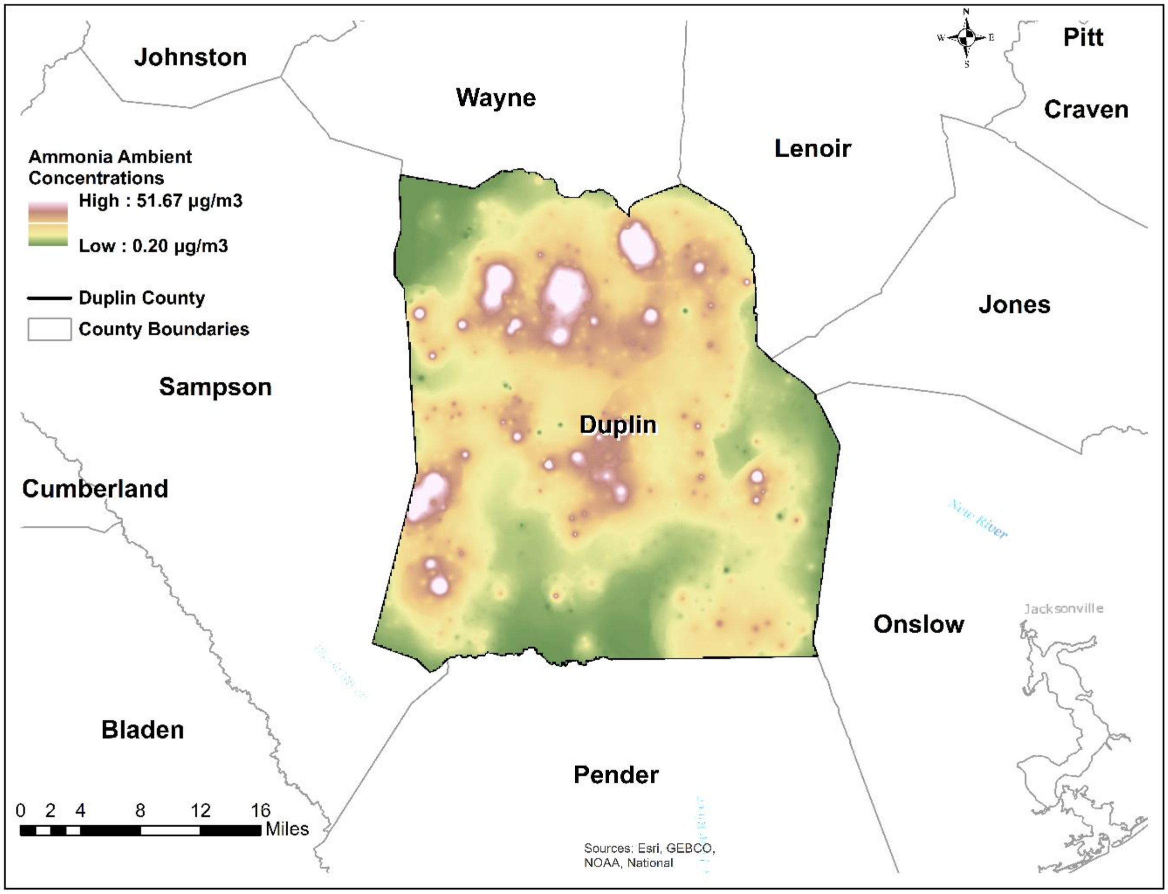

Figure 2. Estimated annual average ambient ammonia concentrations over Duplin County due to the hog CAFO emissions within Duplin County. The maximum ammonia concentration estimated is at 47 µg m^{-3}.

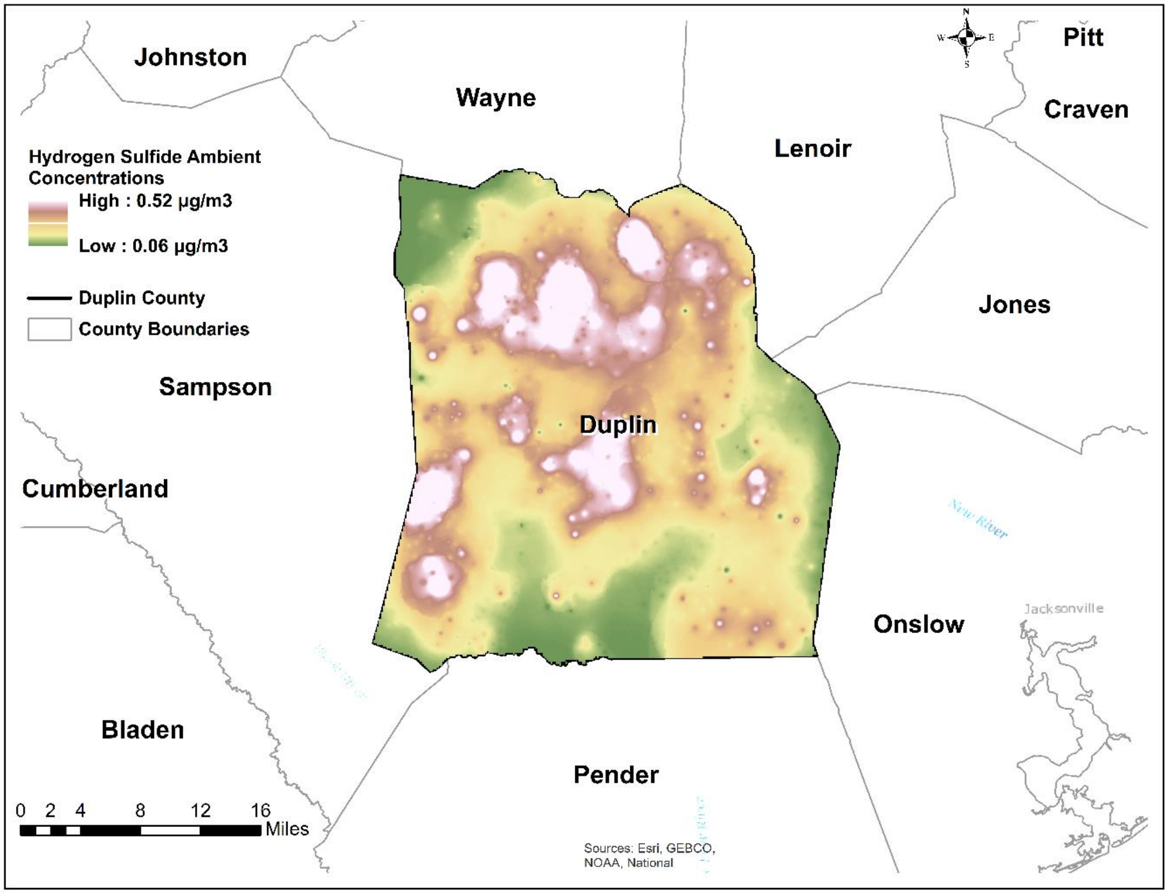

Figure 3. Estimated annual average ambient hydrogen sulfide concentrations over Duplin County due to the hog CAFO emissions within Duplin County. The maximum hydrogen sulfide concentration estimated is at 0.46 µg m^{-3}.

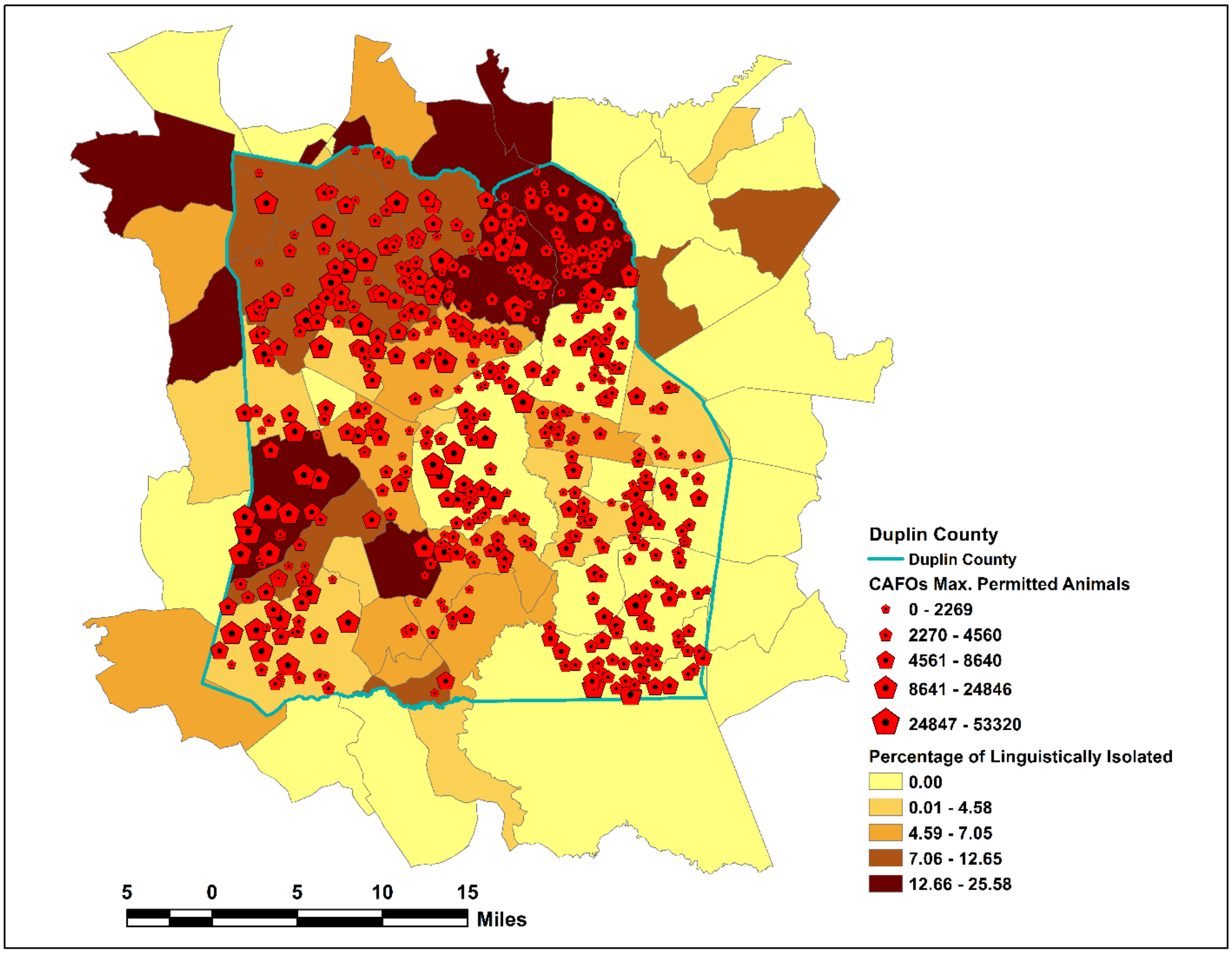

Figure 4. Hog CAFOs distributed in relation to percentage of linguistically isolated for each block group. Block groups within and adjacent to Duplin County are accounted for. Colors indicate the presence of the subgroup within the block group. Duplin County border line in highlighted blue.

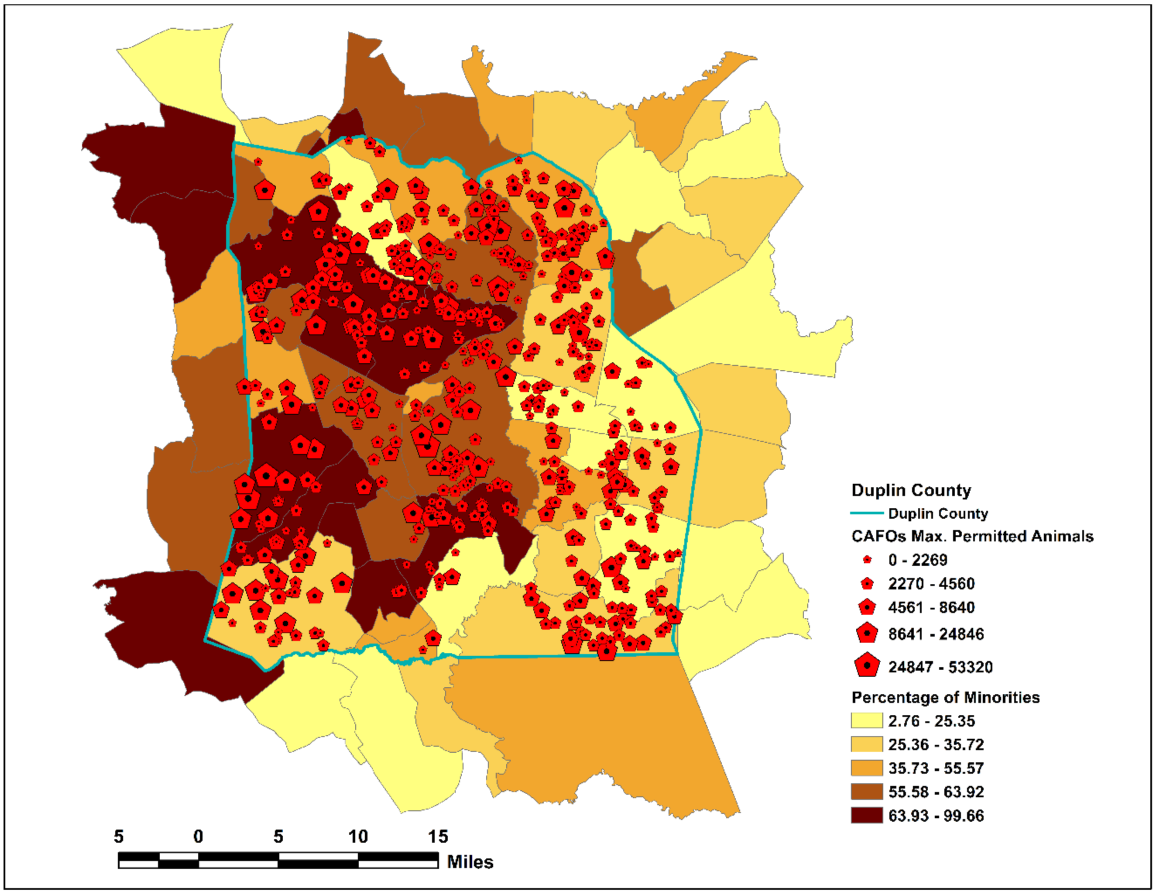

Figure 5. Hog CAFOs distributed in relation to percentage of minorities for each block group. Block groups within and adjacent to Duplin County are accounted for. Colors indicate the presence of the subgroup within the block group. Duplin County border line in highlighted blue.

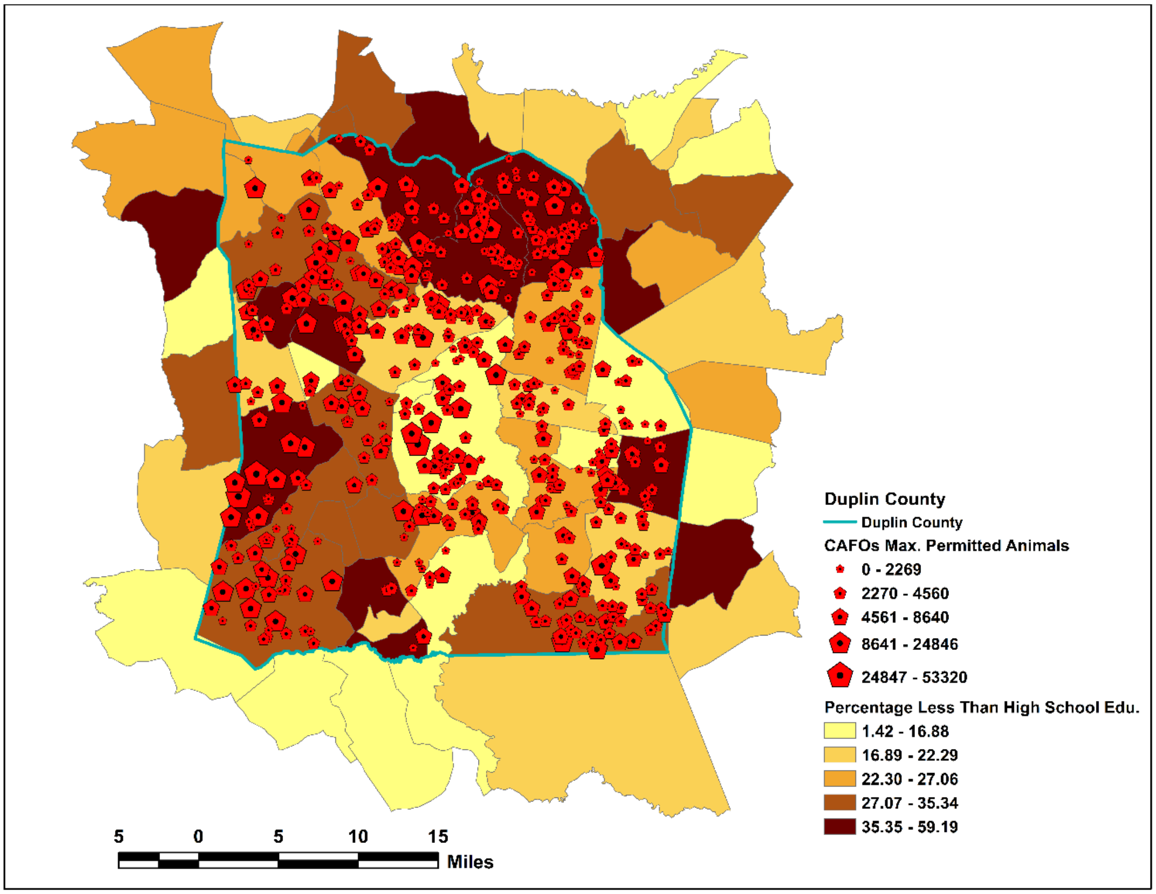

Figure 6. Hog CAFOs distributed in relation to percentage of people with a less than high school education for each block group. Block groups within and adjacent to Duplin County are accounted for. Colors indicate the presence of the subgroup within the block group. Duplin County border line in highlighted blue.

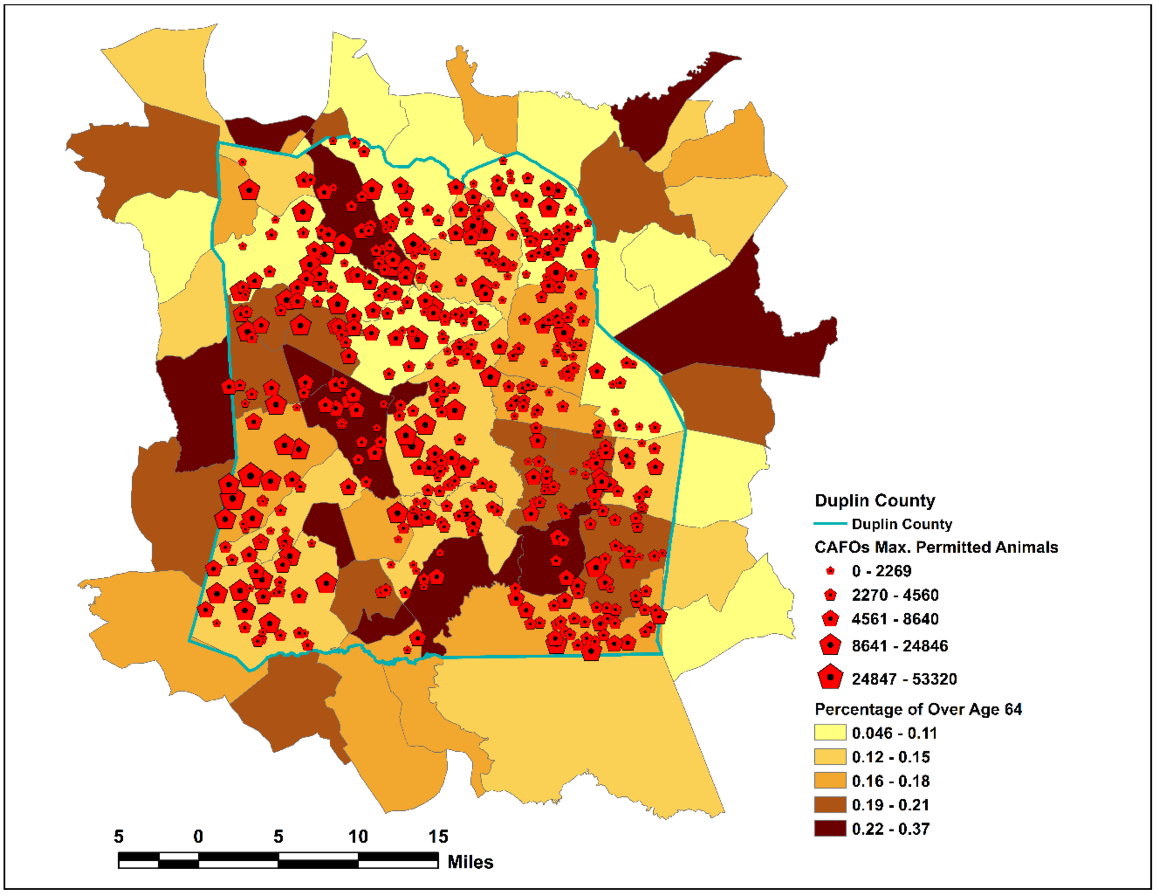

Figure 7. Hog CAFOs distributed in relation to percentage of people over the age of 64 for each block group. Block groups within and adjacent to Duplin County are accounted for. Colors indicate the presence of the subgroup within the block group. Duplin County border line in highlighted blue.

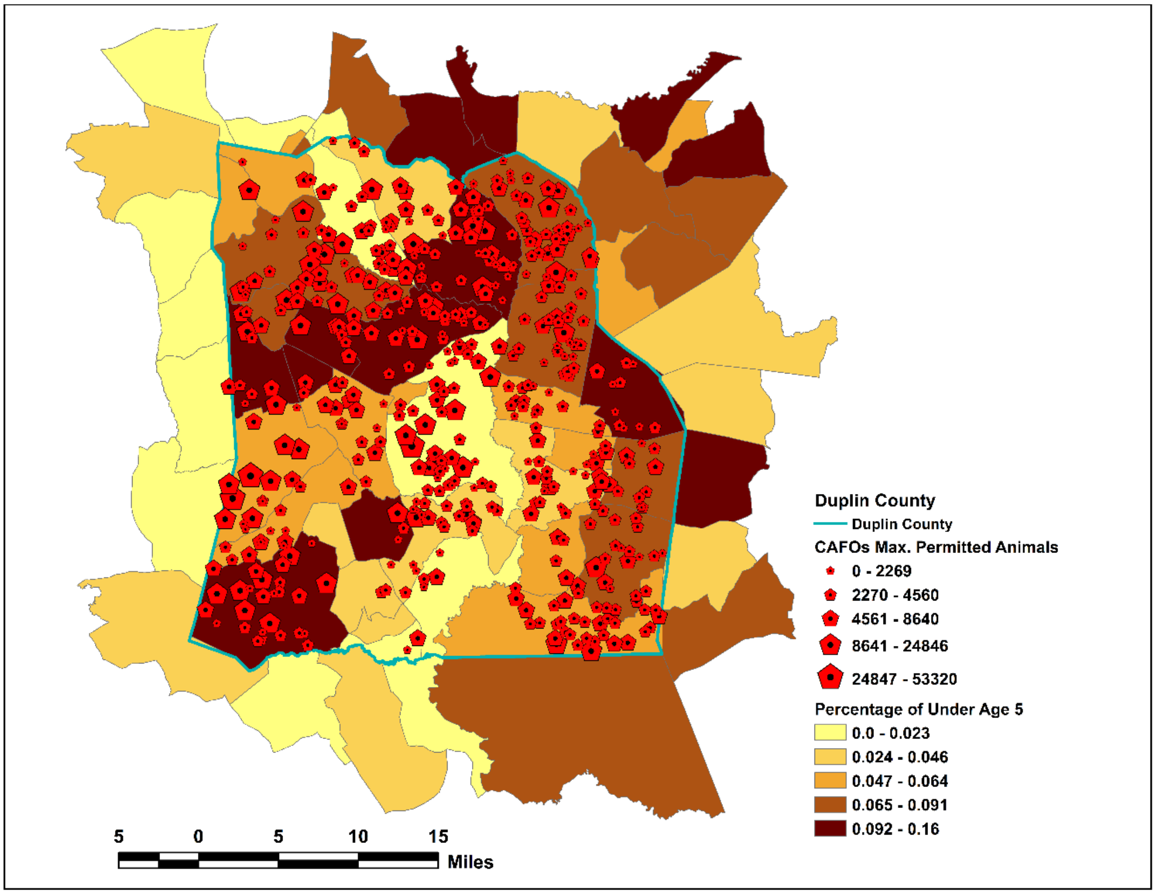

Figure 8. Hog CAFOs distributed in relation to percentage of people under the age of 5 for each block group. Block groups within and adjacent to Duplin County are accounted for. Colors indicate the presence of the subgroup within the block group. Duplin County border line in highlighted blue.

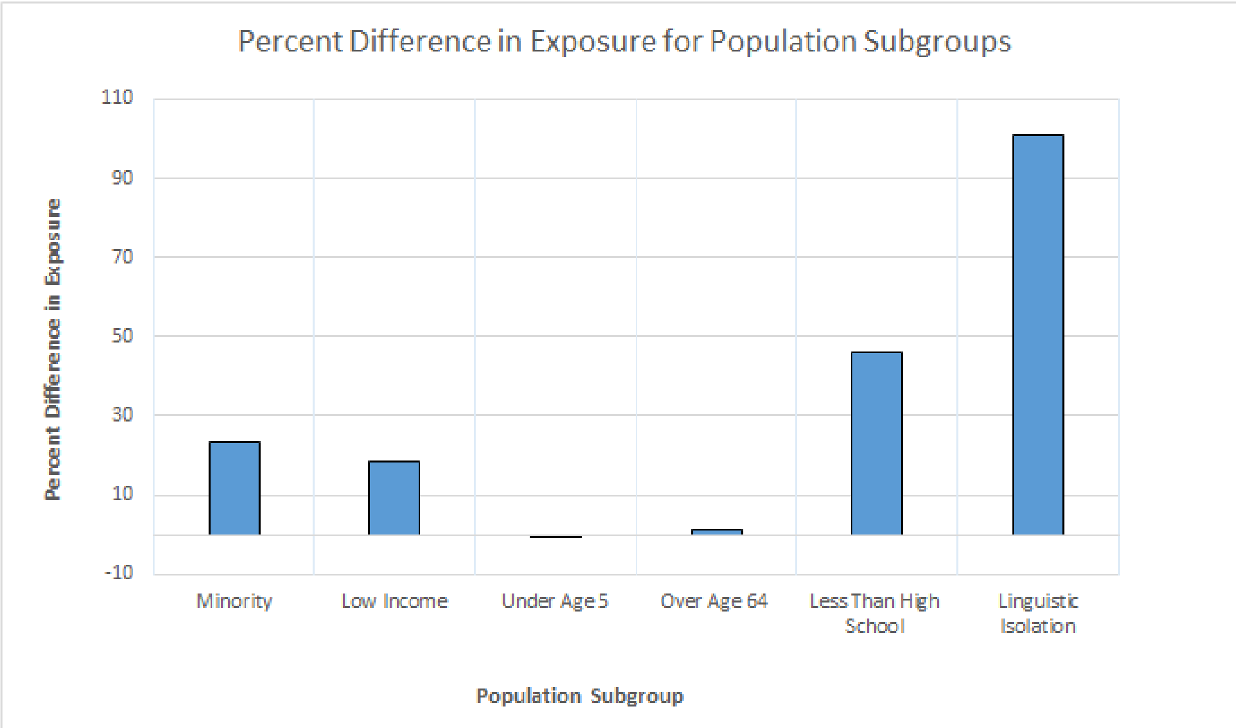

Figure 9. A summary of the percentage differences in exposure by race, age, income, educational attainment, and language from the average population of Duplin County. Comparing minorities, low income, under age 5, over age 64, less than high school education, and linguistic isolation subgroups. On the y-axis, percent difference in exposure of ammonia and hydrogen sulfide from the general population in Duplin. On the x-axis, is the subpopulation of interest.