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Short Communication

Terra incognita: The unknown risks to environmental quality posed by the spatial distribution and abundance of concentrated animal feeding operations

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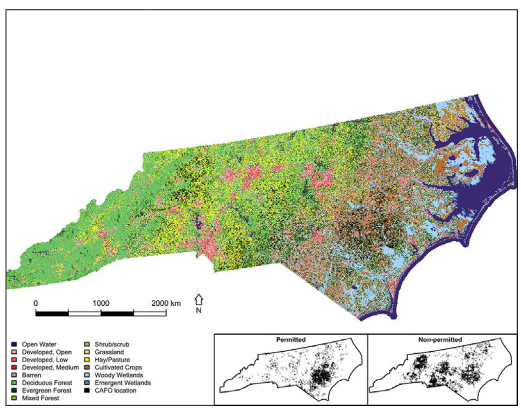
HIGHLIGHTS

- Environmental risk assessments of CAFOs are complicated by a lack of spatial data.
- North Carolina CAFOs are concentrated in the Coastal Plain, subject to large storms.
- 19% of CAFO points (1262) across the state are within 100 m of streams.
- Data gaps prohibit landscape modeling of impacts under changing conditions.

GRAPHICAL ABSTRACT



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ABSTRACT

Concentrated animal feeding operations (CAFOs) pose wide ranging environmental risks to many parts of the US and across the globe, but datasets for CAFO risk assessments are not readily available. Within the United States, some of the greatest concentrations of CAFOs occur in North Carolina. It is also one of the only states with publicly accessible location data for classes of CAFOs that are required to obtain water quality permits from the U.S. Environmental Protection Agency (EPA); however, there are no public data sources for the large number of CAFOs that do not require EPA water quality permits. We combined public records of CAFO locations with data collected in North Carolina by the Waterkeeper and Riverkeeper Alliances to examine the distribution of both permitted and non-permitted CAFOs across the state. Over half (55%) of the state's 6646 CAFOs are located in the Coastal Plain, a low-lying region vulnerable to flooding associated with regular cyclonic and convective storms. We identified 19% of CAFOs ≤ 100 m of the nearest stream, and some as close as 15 m to the nearest stream, a common riparian buffer width for water quality management. Future climate scenarios suggest large storm events are expected to become increasingly extreme, and dry interstorm periods could lengthen. Such extremes could exacerbate the environmental impacts of CAFOs. Understanding the potential impacts of CAFO agroecosystems will require remote sensing to identify CAFOs, fieldwork to determine the extent of environmental footprints, and modeling to identify thresholds that determine environmental risk under changing conditions.

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1. Introduction

Beginning in the mid twentieth century, there was a significant shift in US agriculture toward concentrated animal feeding operations, or CAFOs (Mallin, 2000). The transition from small, family farms to consolidated operations began in the poultry industry during the 1950s, and the model was adopted by swine farmers in the Midwest during the 1970s and 80s. The trend of increasing CAFOs reached the southeastern US in the late 1980s (Mallin, 2000). As a result, North Carolina experienced a nearly four-fold increase in swine inventory from 1975 to 2000 (Yang et al., 2016). Poultry production has increased in North Carolina during the same approximate time period, and the state has been one of the top poultry producers in the United States (Yang et al., 2016). The state Department of Environmental Quality estimated that from 1992 to 2014, poultry inventory increased where it is most concentrated (16% increase Yadkin-Pee Dee River basin, 9% increase Cape Fear River basin), and expanded rapidly in new areas of the state (393% increase Lumber River basin, 331% increase Broad River basin) (Patt, 2017). Although CAFOs provide a rapid and profitable way to provide food to a growing human population, they present significant risks to human health and environmental quality (Burkholder et al., 2007; Greger and Koneswaran, 2010; Mallin et al., 2015). Due to the high volumes of animal waste produced, CAFOs have high potential to contribute to soil, air, and water pollution, posing health risks to nearby communities (Burkholder et al., 2007; Donham et al., 2007; Greger and Koneswaran, 2010; Nicole, 2013). These operations tend to be spatially clustered in areas with environmental regulations and zoning requirements that favor industrial agriculture, particularly the southeastern US (Mallin, 2000) and in rural, impoverished, minority communities (Emanuel, 2018; Nicole, 2013; Wing et al., 2002).

Understanding the impacts of CAFOs and developing and implementing best management practices to mitigate impacts, requires fine-scale spatial data on CAFO locations. Existing research on the spatial distribution of CAFOs and potential impacts to environmental and human health have been conducted at relatively large spatial scales, such as counties (Yang et al., 2016) or watersheds (Harden, 2015). County level agricultural statistics such as the total number of animals housed are available from USDA (https://www.nass.usda.gov/). However, county-scale assessments and similar large-scale studies are not aligned with many ecological processes, and thus are limited in their ability to evaluate the potential impacts of CAFOs on nutrient cycling and water resources at scales that are most appropriate for improving management practices. Data are not publicly or readily available at finer spatial scales or scales more aligned with ecological processes, such as watersheds.

Recognizing the potential environmental and human health risks of CAFOS, some federally mandated best management practices have been developed and implemented. Large CAFOs that meet the EPA definition of >1000 animal units using a liquid waste disposal system are recognized as point sources of pollution and thus, a water quality permit is required (hereafter, permitted CAFOs). Liquid waste disposal is primarily used in swine, egg-producing poultry operations, and some cattle operations. The EPA considers an animal unit to be the equivalent of 1000 pounds of live weight, and large CAFOs are defined as having a minimum of 1000 head of beef cattle, 2500 swine, or 125,000 broiler chickens. The site must also house confined animals for at least 45 days a year and not sustain vegetation during the normal growing season over any portion of the lot to meet the regulatory CAFO definition. CAFO water quality permits regulate waste lagoons, from which liquid waste is generally transferred to a spray field, often of Bermuda grass (Mallin et al., 2015). EPA permitted CAFOs also require Comprehensive Nutrient Management Plans that detail feed, manure, and land management. States can add requirements to permits; for example, all CAFOS are inspected annually in North Carolina. As long as farms maintain a nutrient management plan, spray fields are not regulated by the water quality permit (Centner and Feitshans, 2006). Therefore, the locations or extents of spray fields associated with permitted CAFOs are generally unknown (Patt, 2017). The regulatory assumption is that nutrients and other contaminants from spray fields will remain on site, although this is not always the case (Wing et al., 2002). The environmental risk posed by spray fields is likely underestimated because impacts on agricultural runoff, groundwater recharge, or dispersal of airborne substances cannot be assessed without additional data. Further, public perceptions might not include farmland and spray fields as potential sources of CAFO impacts, resulting in an underestimate of the full risks to their communities posed by this form of industrial agriculture.

Farms with <1000 animal units and CAFOs without liquid waste disposal systems are not regulated in the same way as larger, permitted operations (hereafter, non-permitted CAFOs). Most poultry operations and some cattle operations generate dry litter waste and are thus not required to have water quality permits. In North Carolina, the state Department of Environmental Quality estimates that over 96% of poultry and over 88% of cattle operations use dry waste disposal (Patt, 2017). Waste from these operations is commonly spread on fields as fertilizer, often after transport far from the source farm, complicating the geography of the environmental impact (Patt, 2017).

Our goal was to identify the distribution of potential CAFO risk in a region with high CAFO concentrations as a first step toward improving the ability to evaluate and project the footprint of CAFO land use on environmental quality, including the export of nutrients, microbes, pathogens, and pollutants throughout surface water, ground water, the atmosphere and the terrestrial system. This assessment is also a first step toward assessing the effectiveness of mitigation practices. In some US states, locations of permitted CAFOs are publicly available. For example, an online search identified that Wisconsin, Michigan, Missouri, and North Carolina have publicly available, spatial datasets of permitted CAFOs; however, public records or datasets on the spatial locations are not available for non-permitted CAFOs. In some states, such as North Carolina, private nonprofits (e.g., Waterkeeper and Riverkeeper Alliances) have collected data on non-permitted CAFO locations. As location data are available for both permitted and non-permitted CAFOs, and because of the proliferation of CAFOs throughout the state, North Carolina provides an excellent case study to examine the spatial distribution of CAFOs.

We determined how CAFOs were distributed spatially among and within watersheds in North Carolina. We also evaluated the predominant NLCD land cover classifications surrounding CAFOs. In the United States, the National Land Cover Database (NLCD) is a publicly available dataset that aims to provide information necessary to assess ecosystem health and facilitate nutrient modeling, land use planning, and the development of best land management practices (BMPs) (Homer et al., 2015). The NLCD is scaled to at a 30-m resolution grid and updated every 5 years. Watershed models frequently use NLCD data to inform hydrologic simulations by assuming relationships between land cover and nutrient loading rates, infiltration capacities, or other factors that influence water availability and quality (Karcher et al., 2013). NLCD data layers are considered the most comprehensive, publicly available, datasets of land cover. Previous studies (Burkholder et al., 2007; Rothenberger et al., 2009) have identified the NLCD category "hay/pasture" as animal agriculture and thus, a proxy to identify CAFO locations; however, the EPA defines CAFOs as areas that do not produce crops, forage, or other vegetation. We tested whether CAFO locations are consistently categorized this way or whether they fall into other NLCD categories that are not typically associated with the water quality footprints of CAFOs.

2. Methods

We collected data on permitted CAFO locations from the North Carolina Department of Environmental Quality, which maintains a publicly available spatial dataset (https://deq.nc.gov/cafo-map). Spatial point data for non-permitted CAFOs were shared by the Waterkeeper and Riverkeeper Alliances who created the dataset by inspecting satellite imagery in Google Earth. In the imagery, large, rectangular barns used in poultry operations were identified; therefore, this dataset would not include dry waste cattle operations. We also assume that identification of the distinct geometry of a large, rectangular barn several times longer than its width, or sets of such barns, without manure lagoons is an accurate representation of a non-permitted CAFO. From the dataset, we independently verified 800 randomly selected sites (approx. 20%) using Google Earth Pro imagery set to December 2016, in accordance with the timing of the Riverkeeper assessment. We found that 710 (88.8%) of the points were within the footprint of the facility (on barns or within groupings of barns) and an additional 10.5% were and average of 24.3 m from the facility footprint, less than the width of one NLCD pixel. We found only two points (0.3%) not located adjacent to a farm and three points (0.4%) where barns had been removed but were present in imagery within the previous 2–5 years.

We used the National Watershed Boundary dataset (http://datagateway.nrcs.usda.gov/) to determine the distribution of both permitted and non-permitted CAFOs among major river basins. The National Hydrography Dataset (NHD) (U.S. Geological Survey, 2013) was used to determine the straight-line distance between CAFO points and the nearest stream channel. Then, using the most recent NLCD, 2011, we examined the distribution of land cover classification of CAFO sites.

We determined the land cover at CAFO points by taking the modal (most frequent) land cover from the 2011 NLCD layer within a 50-m buffer of each CAFO point. NLCD data for North Carolina were downloaded from the USGS National Map data platform (TNM Download V1.0: https://viewer.nationalmap.gov/basic/). The NCLD includes 16 different land cover categories derived from Landsat imagery (Homer et al., 2015). The two primary categories for agricultural land cover are cultivated crops, and hay/pasture. The cultivated crops category is defined as actively tilled land or land where annual or perennial crops represent at least 20% of the total vegetation (Homer et al., 2015). The hay/pasture land cover category is defined as areas with at least 20% coverage by grasses or legumes. Some (Burkholder et al., 2007; Rothenberger et al., 2009) categorize hay/pasture as animal agriculture, although the EPA defines CAFOs as areas that do not produce vegetation.

3. Results

3.1. Spatial distribution of CAFOs

North Carolina had a total of 6646 CAFOs as of 2015, including 2679 permitted CAFOs (40%) and 3967 non-permitted CAFOs (60%). Permitted CAFOs were primarily for swine (87%) with a few cattle operations (10%) and few egg producing poultry operations (1%) or other types of operations (2%). Permitted CAFOS are concentrated in the Coastal Plain physiographic region of southeastern North Carolina (2241/2679, 84%, Fig. 1). Non-permitted CAFOS are distributed primarily across the Piedmont (62%) and Coastal Plain (36%).

Half of the permitted CAFOs and 28% of the non-permitted CAFOS were located in the Cape Fear River basin, which is a large (23,735 km^2) basin that drains 18% of the state. Within the Cape Fear, CAFOs are concentrated heavily within the Black River and Northeast Cape Fear River sub-watersheds. Together, the two sub-watersheds drain only 6% of the state land area, but they contain 43% of the state's permitted CAFOs. The Upper Yadkin basin covers only 5% of the state

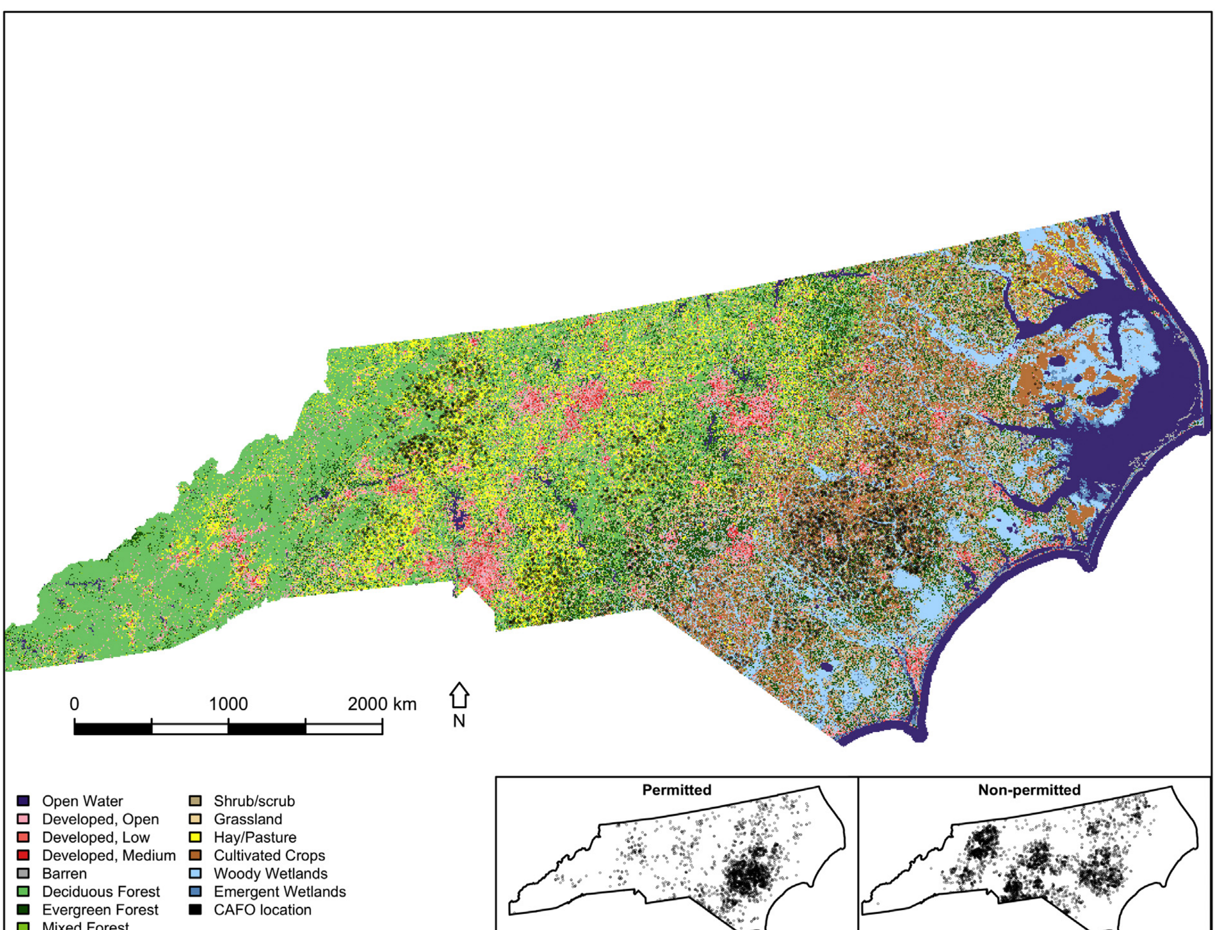

Fig. 1. Locations of CAFOs throughout the NLCD land cover classification of North Carolina.

land area but contains the highest concentration of non-permitted CAFOS, at 11% or 437 CAFOs. The concentration of CAFOs suggests that certain parts of the state, namely sub-watersheds of the Cape Fear and Yadkin River basins, are at higher risk of water quality degradation and other environmental impacts (Fig. 2).

Statewide, half of CAFOs are located within 203 m of a stream (205 m for permitted, 202 m for non-permitted, Fig. 3). We identified 1189 CAFOs (19%) within 100 m of the nearest stream. Of these operations, 67 permitted and 38 non-permitted CAFOs were less than ~15 m (50 ft) from a stream, which is the North Carolina State forestry recommended forest riparian buffer width for perennial water bodies (http://www.ncforestservice.gov/water_quality/bmp_manual.htm). (Aside from forestry, riparian buffer recommendations or regulations vary by watershed within the state). When analyzed by watershed rather than by CAFO type, there was some variability in the median distance to the stream (Fig. 4). Not only does the Northeast Cape Fear watershed contain a high CAFO concentration, but the median distance to a stream was 97 m, and 24 CAFOs were within the 15 m of streams.

3.2. NLCD land cover classification of CAFOs

Previous studies on the environmental impacts of CAFO land use have used the NCLD hay/pasture category is used as a proxy for animal agriculture and CAFO locations (Burkholder et al., 2007; Rothenberger et al., 2009). In our analysis, only 13% of permitted and 42% of non-permitted CAFOs were categorized as hay/pasture. We found that CAFO locations were frequently classified by the NLCD as cultivated crops, including 57% of permitted and 35% of non-permitted CAFOs. Considering both hay/pasture and cultivated cropland, 70% of permitted CAFOs and 77% of non-permitted CAFOs were characterized as an agricultural land cover type by the NLCD.

The remaining CAFOs were primarily classified as natural ecosystems. Thirteen percent of permitted CAFOs and 8% of non-permitted CAFOs were classified as natural terrestrial ecosystems (forest, scrub/shrub, or grassland). An additional 14% of permitted CAFOs and <1% of non-permitted CAFOs were classified as aquatic ecosystems (wetland or open water). Overall, 27% of permitted CAFOs and 8% of non-permitted CAFOs were classified as a natural land cover type by the NLCD. Permitted CAFOs were classified as developed land 3% of the time, but the rate for non-permitted CAFOs was much higher, at 12%. A small number of each CAFO type was classified as barren land by the NLCD (<1%permitted, and 1% non-permitted).

4. Discussion

Proliferation of CAFOs has significantly altered nutrient cycling in the United States (Robertson et al., 2013; Yang et al., 2016). From 1930 to 2012, Yang et al. (2016) identified manure loading increases of 46% for nitrogen and 92% for phosphorus. These increases were spatially clustered as CAFOs proliferated, concentrating manure nutrients in regions including the southeastern US and western Mississippi River basin. North Carolina produces the highest concentration of manure per acre of farmland in the country, (U.S. Enviornmental Protection Agency, 2013), and Yang et al. (2016) estimate manure N and P increased >70% across the state from 1930 to 2012. While this suggests nutrient loading is a spatially clustered environmental risk, the pathways these nutrients and associated manure pollutants (antibiotics, pathogens) take through the terrestrial, aquatic, and atmospheric systems are not well quantified. In a study of small (3.1–45.3 km^2) agricultural watersheds in eastern North Carolina, Harden (2015) found that the presence of CAFOs was often associated with degraded surface water quality. Such studies suggest the need for larger scale studies that

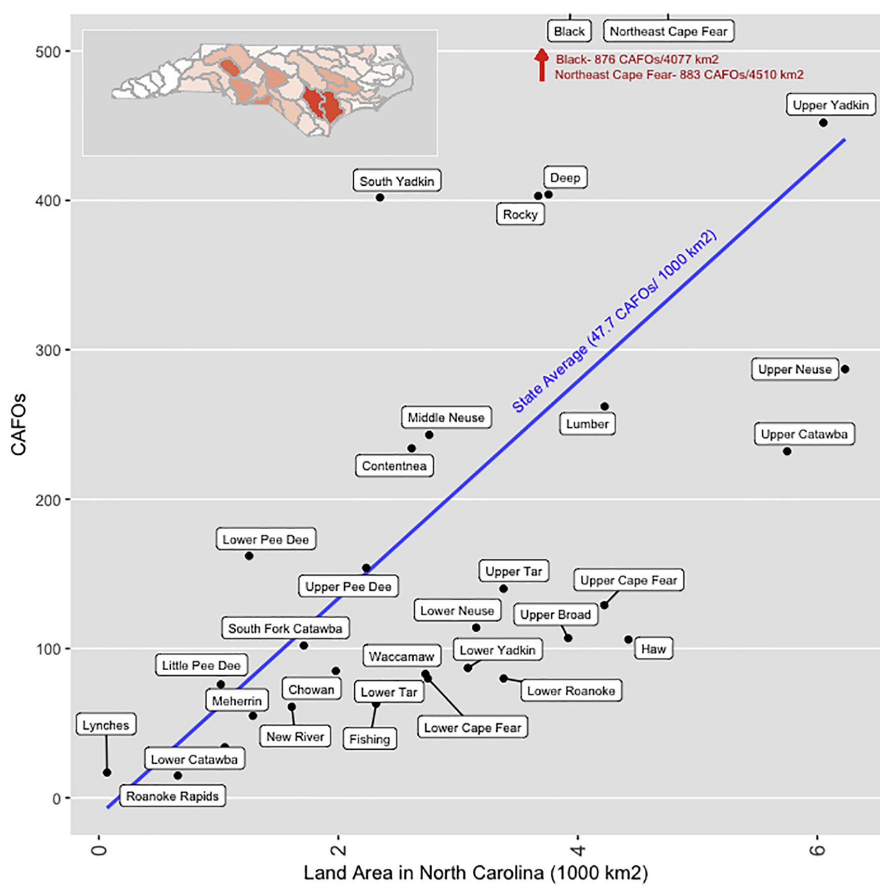

Fig. 2. CAFO density across North Carolina Watersheds. Boundaries are Hydrologic Unit Code (HUC) 8 boundaries designated by the National Hydrography Dataset. Inset map indicates increasingly concentrated CAFO density with darker colors.

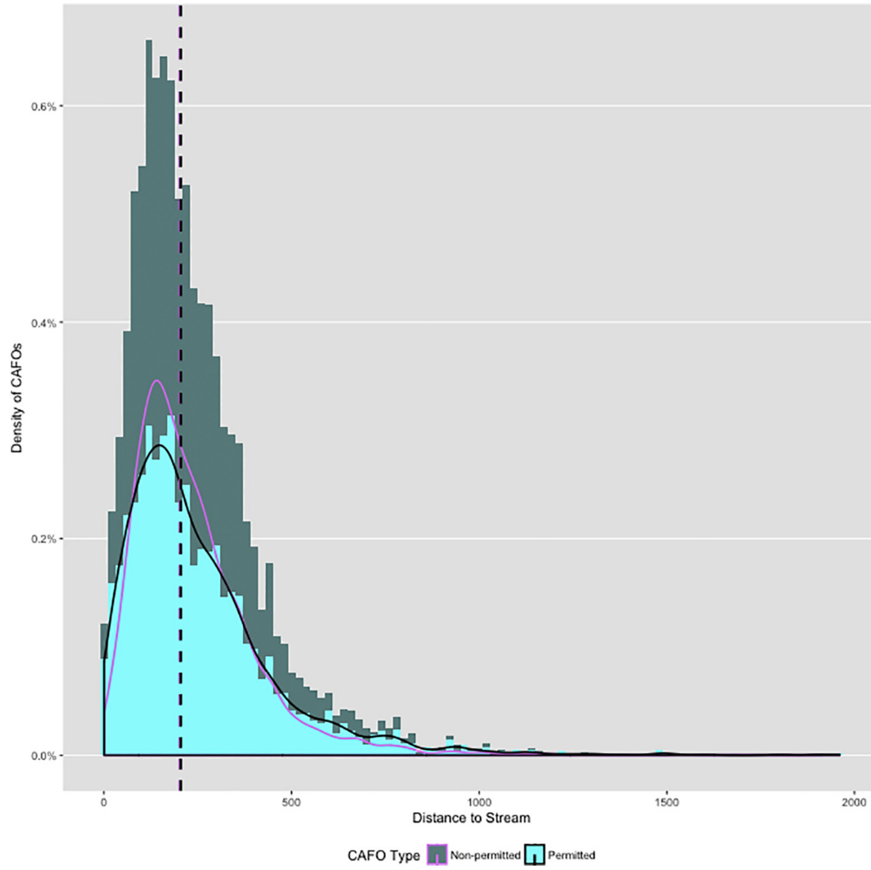

Fig. 3. Distribution of CAFO spatial data points to the nearest stream identified in the NHD database.

assess CAFOs at variable distances to the stream and in multiple land cover types in order to develop and implement BMPs that mitigate environmental impacts.

Our data indicate half of the 6646 CAFO points in the state of North Carolina are within at least 200 m of the nearest stream, and some are within 15 m; therefore, manure-based pollutants may pose a risk to water quality. The magnitude of the risk is not clear, particularly as the location of the points may vary within operations and the overall size of individual operations is not currently quantified. Our analysis included an implicit assumption that the point data are unbiased estimates of facility centroids, but does not include any analysis on the size of operations, which varies and was not available. Much of the data on individual permitted operations are protected as private in the state of North Carolina (Patt, 2017). Non-permitted operations in our dataset were identified using imagery and points are located on barns or within groups of barns, but the number of barns vary for each operation.

Landscape scale studies of the current environmental and human health risks posed by CAFOs would provide the foundation to understand and mitigate impacts in the context of global change. CAFO air quality impacts are known to pose human health risks, causing effects ranging from respiratory symptoms, headaches, nausea, eye irritation (Greger and Koneswaran, 2010; Heederik et al., 2007; Ogneva-Himmelberger et al., 2015; Schiffman et al., 2005). Climate change may exacerbate air quality-related human health risks associated with CAFOs (Fran et al., 2016; Pachauri et al., 2014). Livestock farming emits ammonium (NH_3) and nitrogen oxides (NO_x), which contribute to the formation of particulate matter and tropospheric ozone (Leip et al., 2015), both of which are expected to be problematic under climate change scenarios (Fran et al., 2016). There is a high level of confidence that extreme heat events will increase across the Southeast and that precipitation events will become more extreme. At the same time, tropical cyclones will include heavier precipitation, and likely be more intense (Carter et al., 2014; O'Gorman and Schneider, 2009; Pachauri et al., 2014; Robertson et al., 2013; Wuebbles et al., 2017). Further, regional water stress is expected to increase due to the combination of declining water yields and increasing demand from a rapidly expanding population (Carter et al., 2014; Emanuel, 2018; McNulty

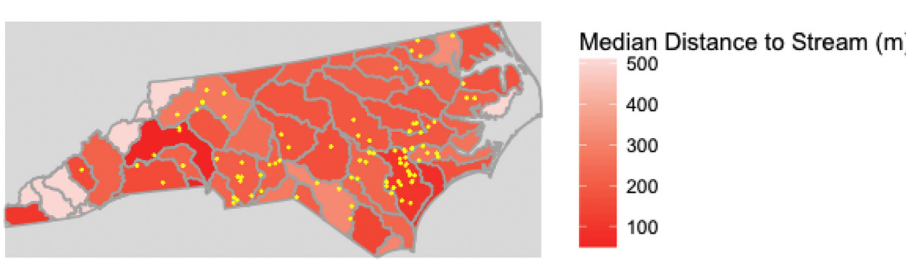

Fig. 4. HUC 8 watersheds coded by median distance between CAFO spatial data points and the nearest stream identified in the NHD database. Points indicate CAFO spatial data points within 15 m (50 ft) of streams, a commonly used riparian buffer distance.

et al., 2013; Sun et al., 2008). To minimize the environmental impacts of CAFOs under increasingly an increasingly extreme climate future, an increased understanding of their distinct environmental impacts is required, including impacts of agricultural stormwater runoff from CAFO barns, lagoons, and waste fields.

In North Carolina, CAFOs are concentrated in the Coastal Plain (Fig. 1), which is particularly vulnerable to catastrophic flooding following hurricanes (Mallin et al., 2002). Since 1990, 15 named tropical cyclones have made landfall in coastal North Carolina and an addition 20 have affected the state without a direct hit. Some of these storms have resulted in flooding and breaching of swine waste lagoons, particularly in the Northeast Cape Fear watershed (Fig. 2), which has one of the highest concentrations of CAFOs in the country (Mallin et al., 2002) and our data indicate many of these CAFOs are very near streams. Mallin et al. (2002) estimated that over 10% of permitted CAFOs were within the area inundated by Hurricane Fran in 1996.

Recognition of the environmental risk posed by CAFOs prompted a moratorium on new or expanding swine operations in 1997, following Hurricane Fran, and this moratorium was made permanent in 2007 (McDonald, 2016). During the most recent tropical cyclone, Hurricane Matthew (October 7–9, 2016), rainfall totals exceeded 38 cm in portions of Eastern North Carolina and the best information available suggests 14 industrial scale swine and poultry operations were flooded, with only two manure lagoons reported breached (McDonald, 2016; Musser et al., 2017). Animal waste contains high concentrations of nutrients as well as antibiotic and pharmaceutical contaminants (Burkholder et al., 2007). Recently, low levels of antimicrobial resistance have been detected in enteric bacteria collected from surface and ground water monitoring sites near CAFOs in the North Carolina Coastal Plain (Casanova and Sobsey, 2016). Catastrophic flooding associated with hurricanes and tropical storms can distribute these and other contaminants far downstream. Therefore, it is important to be able to model the impact of the entire operation, including spray fields that may be flooded or continue to operate during periods of saturated soil (Wing et al., 2002). Substantial data gaps concerning the spatial distribution and size of CAFOs limit the development of projections and other research projects to evaluate the potential impacts of CAFOs associated with catastrophic flooding. Such flooding not only affects surface water quality but poses risk to the large number of residents who depend on private groundwater wells for drinking water (Gibson and Pieper, 2017; Wing et al., 2002). It is possible that the moratorium on swine operations provided some mitigation or at least stabilized the risk. However, there are not sufficient data to determine the impacts of a stable number of swine operations and expanding poultry operations (Patt, 2017). Beyond flood events, long term monitoring is also needed, as animal waste lagoons can leak nutrients into soils and groundwater, reaching problematic levels gradually (Huffman and Westerman, 1995; Mallin, 2000; Ritter and Chirnside, 1990).

Given the widespread use of NLCD data as a spatial proxy for nutrient loading and other water quality parameterizations in environmental models(Almasri and Kaluarachchi, 2007; Karcher et al., 2013; Lehning et al., 2002; Nejadhashemi et al., 2011; Tran et al., 2010), the rate at which CAFOS are considered as natural systems by the NLCD is concerning. Forests and grasslands absorb nutrients and dampen hydrologic extremes by allowing for water percolation into soils, which are not functions provided by CAFOs. Even more than forests, the classification of CAFOs as wetlands in the NLCD is a significant concern for efforts to understand landscape scale nutrient pathways.

Wetlands concentrate and retain excess nutrients, sediments, and other contaminants associated with human activity, and wetland biogeochemical processes such as denitrification and adsorption can transform or sequester potential water contaminants (Zedler and Kercher, 2005). In some ways, CAFOs function as opposites of wetlands; they produce excess nutrients in the form of animal waste, and they often disperse these contaminants over wide areas using wastewater irrigation (Burkholder et al., 2007). Although only 12% of CAFOs in North Carolina are classified as wetlands by the NLCD, these operations could have outsized impacts on water quality in aquatic ecosystems.

5. Conclusions

In the US, there are approximately 450,000 CAFOs, and this form of industrialized agriculture is common in Europe and increasingly being adopted globally (Mallin et al., 2015). A growing body of work highlights tradeoffs between CAFO production and risks to the environment and human health (Burkholder et al., 2007; Donham et al., 2007; Greger and Koneswaran, 2010; Heederik et al., 2007; Mallin, 2000; Mallin and Corbett, 2006; Mallin et al., 2015; Nicole, 2013). However, a full understanding of both the risks and mitigation practices cannot be achieved without finer scale information about this emerging land use type. To this end, we encourage the development of tools and procedures to identify and incorporate CAFOs as a distinct land cover type within landscape datasets such as the NLCD.

The NLCD is produced by the Multi-Resolution Land Characteristics Consortium, a federal interagency organization with missions in science and environmental quality management issues related to land use and land cover https://www.mrlc.gov/about.php. The consortium has taken an adaptive approach since the original NLCD product in 1992, continually updated methods and datasets to improve its representation of land cover. The emergence and expansion of industrial agriculture since 1992, the large size of individual CAFO sheds compared to NLCD pixels, and the distinct waste footprints of these operations all point toward CAFOs as a land cover category that could be incorporated into NLCD. For this to happen, we suggest first steps: 1. Remote sensing studies to identify the spectral signatures of CAFO structures, feedlots, waste lagoons, and wastewater spray fields 2. Field studies to identify the diffusive waste footprints of CAFOs and determine whether there are differences between CAFO type (i.e., swine, poultry, beef) or management techniques to delineate the boundaries of CAFO agroecosystem footprints. These steps can help researchers, managers, and decision-makers move forward with watershed and regional studies of potential CAFO impacts under current conditions as well as scenarios of potential future climate.

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