HHS Public Access

Author manuscript

Sci Total Environ. Author manuscript; available in PMC 2018 February 15.

Published in final edited form as:

Sci Total Environ. 2017 February 15; 580: 865–872. doi:10.1016/j.scitotenv.2016.12.033.

Integrating remote sensing with Nutrient Management Plans to calculate nitrogen parameters for swine CAFOs at the sprayfield and sub-watershed scales

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Abstract

North Carolina (NC) regulates swine concentrated animal feeding operations (CAFOs) using five-year nutrient management plans (NMPs) requiring the plant available nitrogen sprayed (PANspray) to be less than that utilized by crops (PANcrops), i.e. the PAN balance (defined as PANbal=PANspray-PANcrops) remains negative, which avoids over-spraying liquid effluent onto crops. Objectives of this research are first to characterize Duplin County sprayfields and PANbal by creating the first, open-source sprayfield spatial database created for swine CAFOs in NC (for Duplin County). Second, this paper finds that for two sub-watershed scales 199 additional catchments and 1 additional HUC12 were identified as having permitted lagoon effluent applied compared to using CAFO point locations for a total of 510 catchments and 34 HUC12s with swine CAFO sprayfields. Third, a new method disaggregates annual PANbal from NMPs using remote sensing crop data. And finally, probability that sprayfields have excess PANbal is estimated due to k, a PAN availability coefficient. The remote sensing approach finds that 9–14% of catchments in a given year and 24% of catchments over a five year period have a positive PANbal. An additional 3–4% of catchments have probability of a positive PANbal due to variability in k. This work quantifies the impact of crop rotations on of sprayfields at the catchment spatial scale with respect to PANbal and highlights some of the limitations of NMPs have for estimation of PANbal. We recommend that NMPs be permitted based on the crop rotation scenario utilizing the least PAN and that swine producer compliance to manure management practice be encouraged.

Graphical Abstract

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Supporting Information Available

Supporting Information including more detailed descriptions of sprayfield delineation and database standardization as well as supporting tables are available free of charge *via* the Internet at http://pubs.acs.org. Additionally, sprayfield shapefiles (.shp), Google Earth kmz files (.kmz), and associated tables information are freely available online at http://www.unc.edu/depts/case/BMElab/studies/EC_Duplin_CAFO.

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Keywords

Concentrated animal feeding operations; plant available nitrogen; nutrient management; swine; sprayfield

1. Introduction

Swine industrial animal operations, termed concentrated animal feeding operations (CAFOs), are of concern to public and environmental health (Wing *et al.* 2000) due to their effects on respiratory health of neighboring communities (Mirabelli *et al.* 2006), as well as nutrient, pathogen, pesticide, heavy metal and antibiotic resistance trait loads to surface water and groundwater (Burkholder *et al.* 2007; Hribar 2010; Harden 2015; Nadimpalli *et al.* 2014; Mallin *et al.* 2015). Swine CAFOs in North Carolina (NC) customarily store centralized, large volumes of swine waste (i.e. liquid effluent) in open air lagoons and sprayed as fertilizer for crops onto sprayfields. CAFO effects on water quality include lagoon ruptures and breaks during extreme weather events such as during hurricanes, but also chronic water quality impacts which include nutrients carried offsite from sprayfields (Mallin & Cahoon 2003) or from underground drainage tiles (Harden 2004) as runoff or also as groundwater transport of nutrients (Karr *et al.* 2001). Watersheds with CAFOs had a measureable effect on surface water quality with higher total nitrogen compared to control watersheds in a two year USGS study (Harden 2015). In addition to experimental data, a land use regression model found that density of CAFOs is associated with increased groundwater nitrate and may act as reservoir to surface water nitrate recharge (Messier *et al.* 2014).

NC has the second largest hog industry in the United States with 90% of swine CAFOs having 1000 swine or more. Duplin County, NC has the highest density hog-population of any County in the United States (USDA National Agricultural Statistics Service 2012). In NC, environmental safeguards for swine CAFOs regulate nutrients and heavy metals but do not manage swine CAFOs for any microbial or pathogen load. Nutrient regulation is conducted based on NC public law 626 (General Assembly of North Carolina 1995) that created the swine permitting system in NC and an interagency guidance committee provides assistance for creation of nutrient management plans (NMPs).(Hardee *et al.* 2009).

The Animal Operations unit of the Water Resources division of NC's Department of Environmental Quality (DEQ), regulates and permits swine CAFOs, defined as having 250 or more swine, requiring NMPs for each one. The NMPs regulate over application of swine liquid effluent onto sprayfield crops by permitting swine CAFOs if the pounds plant available nitrogen sprayed (PANspray) is less than pounds PAN utilized by sprayfield crops (PANcrops), i.e the PAN balance (defined as PANbal=PANspray-PANcrops) remains negative. A negative PANbal should theoretically ensure that no excess nitrogen is transported to nearby surface water or groundwater. However Messier *et al.* (2014) showed that groundwater nitrogen is higher near CAFOs, but it remains unclear how the aquifer is contaminated. Therefore, work is needed to identify whether there are any catchments with positive PANbal despite the NMPs.

1.1 Objectives

NMPs are a rich data source, however regulatory barriers prevent easy public access to them. Regulatory barriers include the five-year permit review timeframe, public record request protocol, and proposed legislation. Because NMPs are re-submitted every five years, the paper permits are typically housed in DEQ's Central Office Files, and public access requires a staff member to take time to travel to the basement, identify individual animal waste permit files, and deliver them to the person requesting public records. Additionally, extensive public records requests are subject to fees, and in May 2014, although not passed into law, Senate Bill 762 (General Assembly of North Carolina 2014) proposed that aerial photographs and locations of CAFOs, which are in NMPs, be removed from public record.

Currently, the only readily accessible spatial data for an NC swine CAFO is the physical address, latitude and longitude of the CAFO available from DEQ online (NC Department of Environment and Natural Resources 2015). NMPs provide spatial information on the location of sprayfields. Because a swine CAFO almost always includes sprayfields, and watershed boundaries may divide a CAFO's sprayfields, knowing the sprayfield location improves currently known spatial data regarding swine CAFOs and provides more accurate and meaningful data for those studying the effects of swine CAFOs on surface waters.

NMPs also include proposed sprayfield-specific crop rotations and maximum permitted nutrient application data but the plans do not aggregate PAN data at the watershed scale. Identifying watersheds with large volumes of liquid effluent production, i.e. high PANspray and high PANbal, may be beneficial for targeted water quality monitoring and crop rotation management.

Finally, NMPs are unable to disaggregate PANbal by calendar year because NMPs provide multiple approved crop options or rotations throughout the five year permitting process. Remote sensing, however, can be used to identify crops grown on sprayfields for a given calendar year and used to identify PANbal annually.

Objectives of this research are to review all NMP permits in Duplin County to create the first and open source sprayfield spatial database created for swine CAFOs in NC (for Duplin County). Second, this paper quantifies the difference in aggregated PANbal between known CAFO point and newly identified sprayfield locations at two sub-watershed spatial scales in

Duplin County, NC. Third, a new method was developed to identify PANbal on sprayfields using remote sensing data and PANbal was re-calculated annually using sprayfield location in Duplin County between 2010–2014 to identify inter-annual variability. And finally, estimated probability that sprayfields have excess PANbal is identified.

2. Methods

Three methods of calculating PANbal are presented. Two use permitted NMP data and compare CAFO point and sprayfield locations aggregated at two watershed scales. Then, using sprayfield locations, remote sensing identifies crop data on sprayfields to calculate aggregated PANbal at sprayfield and two watershed scales. Point locations of CAFOs regulated by DEQ are publically available online (NC Department of Environment and Natural Resources 2015). Figure 1 displays all CAFOs in NC with an inset of the study area, Duplin County, and displays that swine CAFOs are primarily in eastern NC. DEQ does not regulate dry poultry operations and these facility locations are not publically available.

2.1 Nutrient Management Plan Data Description

Point locations for swine CAFOs are based on the 2015 updated list of permitted swine CAFOs which was obtained from NC DEQ's website in 2015 (see Supporting Information) (NC Department of Environment and Natural Resources 2015). All point locations were manually reviewed by comparing the DEQ-provided latitude and longitude location of a swine CAFO with NMP maps and satellite imagery to ensure correct identification of each swine CAFO. The latitude/longitude points were re-assigned to the centroid of lagoon locations, for the instance in which a swine CAFO had more than one lagoon, or between the hog houses and the lagoon, for the instance in which the swine CAFO had one lagoon. NC swine CAFOs have three types of permits: animal waste swine (AWS), animal waste individual (AWI), and the federal National Pollutant Discharge Elimination System (NPDES) permit for North Carolina Animals (NCA). Of 492 unique swine CAFOs in Duplin County, 483 are AWS, 7 are AWI, and 2 are NCA. A total of seven facilities were removed from this analysis because one AWS facility is not yet built, three AWI permits double as AWS permits, two AWI are zero-animal and have lagoons but no longer have permitted animals, and one AWI is a livestock market with no active sprayfields. Waste management systems for zero-animal facilities were not found and are not included in this analysis. Thus in Duplin County and in this analysis, there are 485 permitted active swine CAFOs in 2015.

To compare PANbal at two spatial scales between CAFO point data and sprayfield data, a spatial database identifying sprayfield areas and corresponding crop and nutrient application parameters was needed to improve estimation of permitted nutrient application at the watershed scale. All Duplin County NMPs were converted into electronic files using hand scanners, data pertaining to sprayfield application of PAN and liquid swine effluent standardized and entered into a database, and NMP maps compared to orthoimagery to delineate sprayfields. Sprayfield delineation was implemented in ArcGIS 10.1.(ESRI 2011) Each delineated sprayfield is linked to the NMP data. Specific methodology for sprayfield database creation and NMP data standardization is identified the Supporting Information.

DEQ requires that NMPs identify the acreage used for sprayfields and provide maps identifying sprayfield location. Although maps are required, many NMPs omitted maps entirely or had poor quality sprayfield identification. In these instances, external data were used to identify location of sprayfields including the Duplin Tax Administration's interactive website to identify owner of the property (Duplin County Tax Administration 2015), the USDA National Agricultural Statistics Service's Cropland Data Layer (CDL) for years 2010–2014 to identify crops grown on the land (USDA National Agricultural Statistics Service n.d.), and soil for Duplin County from USDA's National Cooperative Soil Survey, known as SSURGO (Soil Survey Staff, Natural Resources Conservation Service n.d.). Fields reported as optional fields were omitted from this analysis.

In addition to delineating sprayfields, data from NMPs were compiled. Database standardization followed a procedure for NMP data entry and quality control. Data entered from the NMPs included sprayfield-scale information including sprayfield acreage, total PAN needed by crop per acre, residual PAN per acre, and commercial PAN applied per acre. CAFO-scale information included annual volume of liquid effluent produced, PANspray, PANcrops, PANbal, number of swine, type of swine, NMP year created, and number of leased acres, if any. Because the NMP reports PANbal at the CAFO scale, re-calculation of PANbal for each sprayfield for a given CAFO allowed PANbal disaggregation at the sprayfield scale.

Database standardization was required since NMPs are created by various technicians and are not all formatted or calculated similarly. NMP data use varying technical standards for PANspray, PANcrops, and PANbal based on time the NMP was created. Many old NMPs use technical standards that have since been grandfathered in without recalculating PAN based on present-day technical standards for the estimation of PAN. This analysis used current technical standards (see Crouse *et al.* 2014; North Carolina Interagency Nutrient Management Committee 2014) to re-calculate PAN parameters.

2.2 Remote Sensing Data Description

Although NMPs do not identify the calendar year for which a crop is grown, once the locations of sprayfields are known, remote sensing data were used to identify crops grown on the sprayfields and PANcrops re-calculated per sprayfield for years 2010–2014. Knowing what crop was grown is important for determining PANbal because while some crops, such as corn, require large amounts of nutrients and higher PANcrops, soybeans, a common crop rotated with corn, requires very little nutrients.

Christenson and Serre 2015 (Christenson & Serre 2015) describe the PANcrops calculation using remote sensing to identify crop type using the Cropland Data Layer (CDL) between 2010 and 2014 (years for which CDL was available in NC) and using SSURGO (Soil Survey Staff, Natural Resources Conservation Service n.d.) to identify soil type for each sprayfield. As described in the paper, pounds PANcrops per acre was calculated by matching the crop and soil types identified from the CDL and SSURGO datasets with crop and soil types in a crop yields database created and updated by the NC Interagency Nutrient Management Commission (North Carolina Interagency Nutrient Management Committee 2014). If the CDL identified non-agricultural land on sprayfields, then these sprayfields were omitted from the analysis. Omitted data comprised 3–6% of Duplin county sprayfield acreage between 2010 and 2014. The CDL differentiates soybeans, corn, and pasture. In NC, sprayfield pasture is typically hybrid bermudagrass with crop management options to graze, overseed, or cut for hay. Based on personal communication with Dr. David Crouse, a nutrient management expert and soil scientist, most hybrid bermudagrass is overseeded and so all CDL-identified pasture was classified as overseeded hybrid bermudagrass. Table S1 in the Supporting Information provides the full table of reclassified crops identified by the CDL and matched to the crop yields database (previously published in Christenson and Serre 2015).

2.3 Metrics

2.3.1 Calculating PANcrops—PANcrops (Equation 1) is an estimate of how much nitrogen, in pounds, is needed by sprayfield crops to grow and is calculated based on a crop yield database managed by the NC Interagency Nutrient Management Committee (North Carolina Interagency Nutrient Management Committee 2014) where slope is a slope correction coefficient, RYE is the realistic yield estimate, N is a nitrogen factor per acre, acres is the sprayfield acreage all for a given crop type, c, and soil type, s.

$$PAN_{crops}=\sum_{i=1}^{n} slope_{s,c} * RYE_{s,c} * N_{s,c} * acres \quad \text{Equation 1}$$

NMPs report annual PANcrops needs for varying crop rotation scenarios proposed. PANcrops was assumed to come entirely from liquid effluent PAN, rather than supplemented or replaced with commercial fertilizer, which is needed when phosphorus builds up in the soil. For this analysis, if several crop rotations are allowed in a permit, we used the crop rotation utilizing the least PAN (smallest PANcrops) in order to obtain the largest (i.e. worst case scenario) PANbal that is allowed by that permit.

2.3.2 Calculating PANspray—NMPs provide the estimated total PANspray produced by a swine CAFO. PANspray is the estimated portion of total nitrogen in swine manure that remains available for crops to use after spraying the liquid effluent onto the sprayfield. PANspray is a difficult quantity to estimate because the total nitrogen content of swine manure is not all plant available since some nitrogen is volatilized into the atmosphere while in the lagoon and while being sprayed onto fields during irrigation. PANspray also depends on other variables such as humidity, temperature, wind speed, and precipitation. Estimated PAN produced by the CAFO is also dependent on the irrigation type but for Duplin County, all NMPs reported broadcast (i.e. sprayfield) irrigation systems.

Equation 2 is the average estimated PANspray for a given swine CAFO, as given in the NC Agricultural Chemicals Manual for 2015 (Crouse *et al.* 2014).

$$PAN_{spray}=n_i * V_i * N_i * k \quad \text{Equation 2}$$

Although other variables may be important for determining PANspray for each sprayfield, PANspray is based on number of swine of type i (i.e. life-stage, e.g. farrow to wean or feeder to finish), V as the accumulated manure or liquid effluent volume of swine of type i in 1000 gallons per year, N as the total nitrogen per 1000 gallons of lagoon liquid produced by swine type i, and k as the estimated fraction of total nitrogen applied to a sprayfield that becomes plant available for a given irrigation type. The PAN availability coefficient, k, is estimated to be 0.5 for broadcast irrigation sprayfield systems indicating that 50% of nitrogen that is in liquid effluent exiting the lagoon and to be sprayed onto the fields is lost due to volatilization before reaching the crops (Crouse *et al.* 2014) or is organic, particulate nitrogen unavailable for plant absorption, i.e. 50% of nitrogen being sprayed is considered plant available. Additionally, PANspray does not take into account atmospheric deposition of ammonia after volatilization.

For this analysis, PANspray was calculated using Equation 2 rather than incorporating older on-farm records from NMPs primarily because on-farm records were outdated (usually over a decade old). It should be noted that the vast majority of NMPs calculate PANspray using older technical standards and this analysis uses up-to-date recalculations.

Because PANspray is reported for the entire CAFO rather than for individual sprayfields, PANspray was recalculated for each sprayfield. Instead of apportioning PANspray by sprayfield acreage or evenly across sprayfields, PANspray was apportioned to a CAFO's sprayfields based on the sprayfield's PANcrops. Sprayfields with crops requiring higher PANcrops, were apportioned higher PANspray. The sum of PANspray for a CAFO's sprayfields is equal to the total PANspray in the CAFO's NMP.

2.3.3 Calculating PANbal—NMPs are regulated such that the PANbal must be negative to be in compliance with DEQ. The PANbal equals PANspray minus PANcrops. A positive PANbal represents PAN that cannot be absorbed by the crops currently grown on the sprayfield. NMPs report average annual CAFO-scale PANbal. Each sprayfield's PANbal was calculated by subtracting the sprayfield's reported PANcrops from the sprayfield's calculated PANspray.

2.4 Sub-Watershed Aggregation

For permitted CAFO point data, and permitted and remotely sensed sprayfield-scale data, the metrics PANspray, PANcrops, and PANbal were summed over two sub-watershed scales for any sub-watershed that intersects or is within Duplin County which includes 1134 catchments averaging 529 acres apeice from the National Hydrography Dataset (USGS & EPA 2012) and 34 USGS-defined sub-watersheds at the "HUC12" scale averaging 20704 acres.(USGS & USDA - NRCS n.d.) Sprayfields that crossed into more than one sub-watershed had all PAN values weighted by proportion of acreage in each sub-watershed.

2.5 Probability PANbal >0

DEQ uses a value of k equal to 0.5 in its NMP calculations, as reported in Crouse *et al.* (Crouse *et al.* 2014) and presented in Equation 2. However other studies assessing the percent total nitrogen volatilized during sprinkler application of swine liquid effluent have reported a range of values. Whalen *et al.*(Whalen & DeBerardinis 2007) report the highest value of nitrogen availability at 95% (i.e. 5% total nitrogen loss) while Sharpe *et al* (Sharpe & Harper 1997) report that very little total nitrogen remains in the soil after spraying with only 24% remaining available for plant uptake. This suggests that k is a major source of variability in reported PANbal, the difference of PANcrops and PANspray.

To assess variability in PANbal due to k, the variability in other variables used in the calcualation of PANbal was assumed to be zero. i.e. in the calculation of $PAN_{bal} = n_i * V_i * N_i * k - PAN_{crops}$ we assume no variability in the number of pigs on a CAFO, in the volume of liquid effluent produced, in the amount of total nitrogen in the liquid effluent, or in the PANcrops calculated for a given crop on a given soil type. The standard deviation (SD) of PANbal, SD[PANbal], is then given by

$$SD[PAN_{bal}]=n_i * V_i * N_i * SD[k] \quad \text{Equation 3}$$

where n_i is number of pigs reported in the permit, V_i is the volume of liquid effluent produced by type of swine reported in the permit, $N_i = PAN_{spray,i}/n_i * V_i * 0.5)$ is the amount of total nitrogen in the liquid effluent that is back-calculated from the $PAN_{spray,i}$ reported in the permits, and $SD[k]$ was set to a value of 0.1775 calculated by assuming that k is normally distributed with a standard deviation equal to 1/4th of the 95% interval calculated as the difference between the highest (0.95)(Whalen & DeBerardinis 2007) and lowest (0.24)(Sharpe & Harper 1997) values published for k.

The probability that PANbal >0, i.e. that all PANspray is not absorbed by crops, is then calculated by assuming that PANbal is normally distributed with a mean equal to the calculated $PAN_{spray} - PAN_{crops}$ and a standard deviation given by Equation 3.

3. Results and Discussion

3.1 Characterization of Duplin County NMPs

Sprayfield shapefiles (.shp), Google Earth kmz files (.kmz), and associated tables information are described in the Supporting Information and freely available online.

Duplin County has 24,528 permitted sprayfield acres receiving lagoon effluent and over two million swine producing almost two billion gallons of liquid swine effluent per year corresponding to 3.3 million pounds of annually permitted PANspray (Table 1). All NMPs in Duplin County use a broadcast irrigation system and none of the NMPs in Duplin County incorporated PAN from dredged lagoon sludge into their PANbal. The average age of Duplin County NMPs submitted in 2014 is seven years (created in 2007), with nearly one third of NMPs created one decade before the 2014 submission and some as old as 1996, when DEQ first began permitting swine CAFOs.

Sprayfields in Duplin County range from being located directly next to lagoons and CAFO centroid locations to being up to four miles from the CAFO centroid. The majority (63%) of sprayfields are located less than a quarter mile from CAFO centroids, however 8% of sprayfields are located over half a mile from the CAFO centroid.

While creating the NMP database, there were inconsistencies between NMP format and nutrient parameter estimation including PANcrops technical standards, which crop-rotation scenario PANbal used for compliance purposes, and whether on-farm analysis of PANspray was used. Recommendations for a regulatory perspective include the following: PANcrops (and thus PANbal) should be calculated using crop rotation scenario utilizing the least PAN (i.e. the annual crop rotation scenario in which PANcrops is the least) and on-farm analysis of PANspray should not be used if no longer applicable (i.e. out-dated). Additionally not included in NMPs at all is the PAN from sludge dredged up from lagoons and also applied to sprayfields. Location of sludge application is needed to ensure that PANbal on a sprayfield and watershed scale remains below zerio.

3.2 Comparing CAFO Point to Sprayfield

As a result of using the sprayfield spatial database, 199 additional catchments and 1 additional HUC12 were identified as having permitted lagoon effluent applied for a total of 510 catchments and 34 HUC12s with swine CAFO sprayfields compared to only using CAFO point locations. Of 311 catchments with swine CAFOs, 30% of catchments varied by at least 50% and 50% of catchments varied by at least 25% for aggregated PANbal when compared to aggregating PANbal using sprayfield location. Figure 2 displays change in pounds PANbal aggregated at the catchment and HUC12 sub-watershed scales for point locations (left) compared to sprayfield locations (right) with a middle column displaying the difference (labeled in percent difference) between point and sprayfield location. The PANbal difference identifies sub-watersheds that have a more positive shift, indicating PANbal has increased and has less crop availability to absorb PANspray nutrients. Dark grey sub-watersheds distinguish identified sub-watersheds as a result of using sprayfield location. Smaller spatial scales have more variation compared to the larger HUC12 sub-watershed scale.

In addition to presenting spatial distribution of PANbal/acre at two sub-watershed scales, Table 1 compares number of swine, sprayfield acreage, accumulated manure, and the average values of PANspray, PANcrops, and PANbal at the CAFO, catchment, HUC12, and county scales.

3.3 Remote Sensing Approach

Using PANbal calculated based on sprayfield locations we calculated the number of catchments with sprayfields having PANbal greater than zero under various scenarios (Table 2).

The first scenario (Figure 2) is based on the NMP crop rotation scenario utilizing the least PAN (i.e. allowing the highest PANbal). Under that scenario we identified 2% (n=11) of 510 catchments with PANbal>0 (Table 2) indicating that 2% of catchments have sprayfields where excess nitrogen application is permitted in some years, which can lead to long-term contamination of surface water and groundwater.

The second scenario calculates PANbal based on the crop that is identified using remote sensing in the years between 2010 and 2014 (Figure 3). Remote sensing compares PANbal between crops that are actually planted and crops that are permitted in the NMPs. We found that 9–14% (n=44–72) of catchments have PANbal>0 based on remote sensing in years 2010–2014, which is a substantial increase compared to the 2% of catchments found to have PANbal>0 based on what is permitted in the NMPs (Table 2). This large increase is due to NMPs requiring exact implementation to be effective, and a small difference between the crop that is planted versus that permitted can lead to large change in PANbal. Hence the failure to correctly implement the NMPs is another large potential source of surface water and groundwater contamination, and remote sensing provide an ideal tool to ensure correct implementation of the NMPs through precision agriculture.

Although in a given year remote sensing found that 9–14% of catchments may have PANbal>0, over a five year period up to 27% (n=140) of catchments with sprayfields in Duplin County have at least one year among 2010–2014 for which PANbal>0. Of these 140 catchments with at least one year having PANbal>0, 53% of them have exactly 1 year, 24% have exactly 2 years, 9% have exactly 3 years, 4% have exactly four years, and 9% have all 5 years for PANbal>0 exceedance. Although the same amount of PANspray is permitted annually in an NMP, PANcrops vary annually and thus PANbal changes from year to year at the catchment and HUC12 sub-watershed scales as displayed in Figure 3. Inter-annual variability in PANcrops for a given spatial scale can be explained by common corn-soybean rotations in which soybeans do not require much PANcrops for a calendar year while corn requires much more PANcrops in the next calendar year.

Table S2 in Supporting Information identifies average PANspray, average PANcrops, and average PANbal for years 2010–2014 at the catchment and HUC12 sub-watershed scales as calculated using the CDLs compared to reported NMP values.

The largest limitation in the remote sensing approach is crop validation. The total average PANcrops identified by using remote sensing CDL data is 6.2 million pounds of PAN compared to 5.5 million pounds as permitted by NMPs, a 13% increase. However, increased total PANcrops identified in remote sensing compared to total PANcrops reported in NMPs would bias PANbal more to the negative and does not explain the increase in catchments with PANbal>0 using the remote sensing approach. Duplin County delineated sprayfield acreage is 17% more than reported NMP acreage which may account for higher PANcrops than reported. For corn, as discussed in Christenson and Serre 2015, (Christenson & Serre 2015) the 2012 CDL for Duplin County reports 16% more corn compared to known corn production in the USDA 2012 agricultural census. The CDL’s internal crop identification validation identifies that corn is correctly identified 95% of the time. Soybeans also have a low CDL mis-identification error.

In addition to reported remote sensing sensitivity and specificity error, CDL cannot differentiate among crop or manure management options which have resulting differences in PANcrops. Remote sensing cannot incorporate specific waste management or crop management decisions to modify PAN calculations (e.g growing hybrid bermudagrass for hay or for grazing).

3.4 Calculating Probability of excess PANbal

Assessing the uncertainty that describes the variability in the nitrogen availability coefficient, k, allows error in PANspray and thus also PANbal to be estimated. In doing so, we quantify the number of catchments that may have PANbal>0 due to variability in k from sprayfield to sprayfield under varying spray and climatic conditions. As discussed, Burkholder *et al.* find that elevated nutrients in surface water are found from lagoon seepage and surface runoff from sprayfields even when liquid effluent is applied at recommended application rates (Burkholder *et al.* 2007).

Quantifying probability of the failure of PANbal, P[PANbal>0], due to variability in k can be determined for catchments that do not have PANbal>0, that is, P[PANbal<0.5] (see Table 2). We find that in addition to catchments with P[PANbal>0.5], an additional 3–4% (n=16–21) of catchments were identified as having probability of having a positive PANbal due to k after multiplying the lower bound of probability by the number of catchments classified within that probability. For example, when using the lower limit of the probability for NMPs (from Table 2), 9 catchments have a 40% probability of PANbal>0, 11 with 30%, 16 with 20%, 83 with 10%, and 380 with 0%. Thus for NMPs in addition to the 2% of catchments with P[PANbal>0]>0.5, 9 additional catchments with P[PANbal>0]<0.5 are expected to have PANbal>0.

Although we assess the variability in one coefficient, k, in the calculation of PANbal, other sources of variability are not accounted for in PANspray or in PANcrops. For instance, NMPs quantify PANspray of produced lagoon sludge, but do not incorporate this value into the permitted PANbal. Also, although nitrogen in liquid effluent (N) is adjusted for swine type, the variability in N is not accounted for. Assessment of additional variability in PANspray would increase the variability in PANbal and increase the probability that catchments would have a positive PANbal.

For PANcrops, variability not accounted for has been identified to bias PANbal more to the negative since using remote sensing calculates 13% more total PANcrops than NMP-reported PANcrops in Duplin County. For NMP calculation for PANcrops, RYE determines how much nitrogen a crop will use to grow to maturity on a given soil type, which assumes that crops grow to harvestable maturity and does not account for years in which there may be higher incidence of drought or disease which would cause under-utilization of nitrogen. RYE values are based on the average value of three of five years of data and assumes that poorly drained soils have sufficient artificial drainage. However as PANcrops increase, PANbal decreases and so biases PANbal to be more negative.

Even if all variability in calculation of PANbal were accurately quantified, swine producer NMP implementation behaviors may be more significant in determining PANbal exceedances on a sprayfield spatial scale. For example, NMPs identify best manure management practices to protect water quality such as liquid effluent is not permitted to be sprayed before rain events or when soils are saturated. Swine producer adoption of precise sprayfield-specific waste management described in nutrient management plans is unknown, however surveys conducted with NC farmers (Osmond *et al.* 2015) found that nitrogen was just as often under-applied as over-applied and nutrient management plans were not the primary basis for how to fertilize their fields due to distrust of government and universities and the desire to use nitrogen as insurance in case of increased yield. Additionally, lagoon management may take priority over crop fertilizer needs due to insufficient freeboard requiring waste spraying. Lagoons are required to have sufficient headboard, so swine producers may spray liquid effluent before severe rain events and before hurricane season. Thus the amount and timing of PANspray application may not ideally correspond to crop needs.

4. Conclusions

NMPs permit CAFOs for PANspray that does not outweigh PANcrops such that PANbal remains negative, however there are failures in the permitting system that can lead to an excess PANspray applied, which results in a positive PANbal with possible leaching or overland flow of nutrients into groundwater and surface water.

This paper identifies that spatial data regarding sprayfield location compared to swine CAFO location improve estimation of liquid swine effluent application and associated nutrient parameters at sub-watershed scales in Duplin County, NC. As a result of using the sprayfield spatial database, 199 additional catchments and 1 additional HUC12 were identified as having permitted lagoon effluent applied for a total of 510 catchments and 34 HUC12s with swine CAFO sprayfields compared to using CAFO point locations.

Additionally, this work quantifies the impact of crop rotations on changes in PANbal finding that 2% of catchments have PANbal exceedances permitted in NMPs. Thus, averaging a CAFO's PANbal over multiple years for multiple annual crop rotations hides the inter-annual variability in PANcrops and the potential for PANbal>0 in some years. Using remote sensing to calculate PANbal from crop type on sprayfields finds that 9–14% of catchments in a given year and 24% of catchments over a five year period in Duplin County have positive PANbal. Differences in PANbal for catchments between the remote sensing approach and permitted in NMPs are due to the PANcrops calculations with crops identified by remote sensing different from crops permitted in the NMPs. Remote sensing is able to disaggregate averaged PANcrops by year and allows retrospective evaluation of nutrient parameters for watersheds by estimating which calendar years have higher PANbal including exceedances.

We highlight some of the difficulties in estimating PANbal primarily to assumptions in the estimation of the *k* parameter for PANspray. We find that due to the variability in k, an additional 3–4% of catchments in Duplin County have a probability of PANbal>0.

Due to variability in calculation of PANbal, we recommend that PANbal in NMPs be based on the crop rotation scenario utilizing the least PAN and that PAN from sludge be incorporated into NMP PANbal calculations. Additionally, rather than increasing acreage required or reducing number of swine produced to ensure that PANbal is negative, crops with higher PANcrops can be planted. Finally, non-point source nitrogen pollution may be prevented by ensuring river buffers are in place (Christensen *et al.* 2013) as well as increased technical support and individualized attention from experts for increased adoption and full implementation of precision waste management outlined in NMPs (Osmond *et al.* 2015).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Funding Support

This work was supported in part by the American Association of University Women, by the joint NSF-NIH-USDA Ecology and Evolution of Infectious Diseases program [grant number 1316318], and NIH training grant [grant number T32ES007018]. We thank staff members at the NC DEQ Animal Operations Division C. Lawson, J.R. Joshi, M. Garoma, and K. Prather for logistical considerations while analyzing nutrient management plans, D. Crouse at NC State University for extensive technical help regarding nutrient management plan creation and plant available nitrogen calculations, two anonymous reviewers for their extensive comments to improve this manuscript, and to all of the unpaid scanning and spatial database creation volunteers in the Nutrient Management Plan Team including E. Armstrong-Carter, G. Boles, J. Cordes, C. DeStefano, D. Holcomb, J. Lin, A. McGee, J. McMath, M. Napier, S. Phelps, S. Rhodes, J. Rinsky, J. Santos, P. Stovall, N. Shah, W. Yaniero, J. Zhou, N. Ziegl, and others.

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Highlights

- Remote sensing identifies annual nitrogen parameters for swine sprayfields.
- Using sprayfield instead of farm location improves estimates for swine wastewater.
- Crop rotations impact sub-watershed scale nutrient balance.

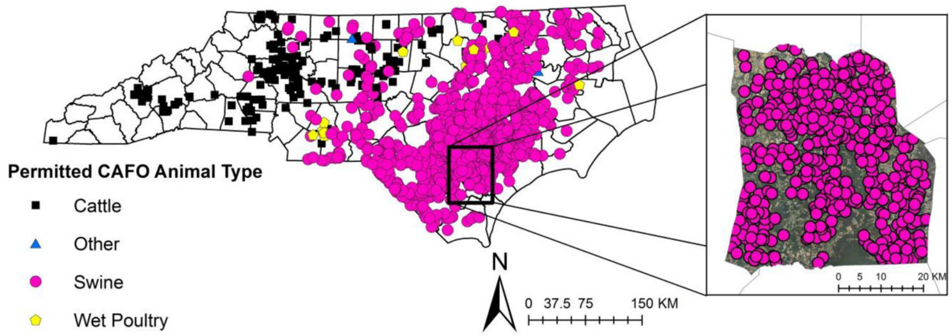

Figure 1.
All 2015 CAFOs permitted by DEQ in NC with an inset of the study area, Duplin County

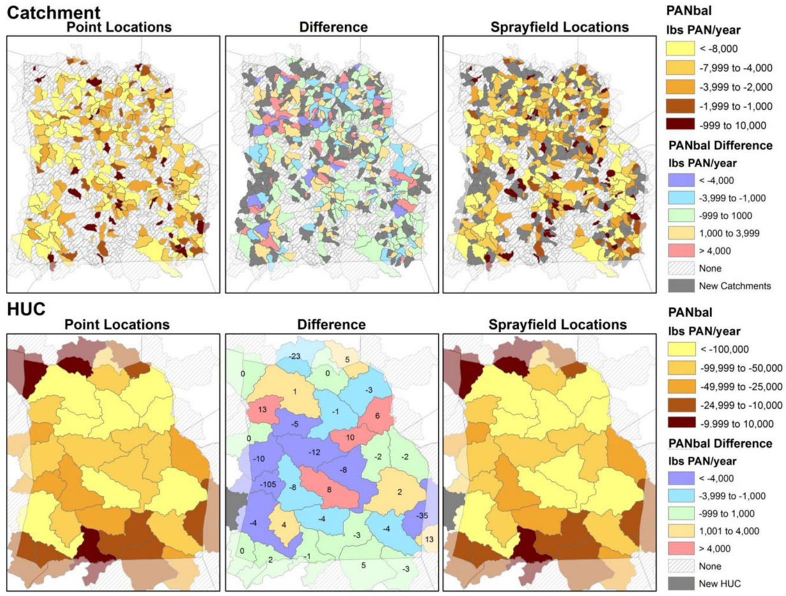

Figure 2.
Comparing pounds PANbal at the catchment and HUC12 sub-watershed scales using point vs. sprayfield locations and permitted data. Difference identifies shifts in sub-watersheds with labeled numbers identifying percent change

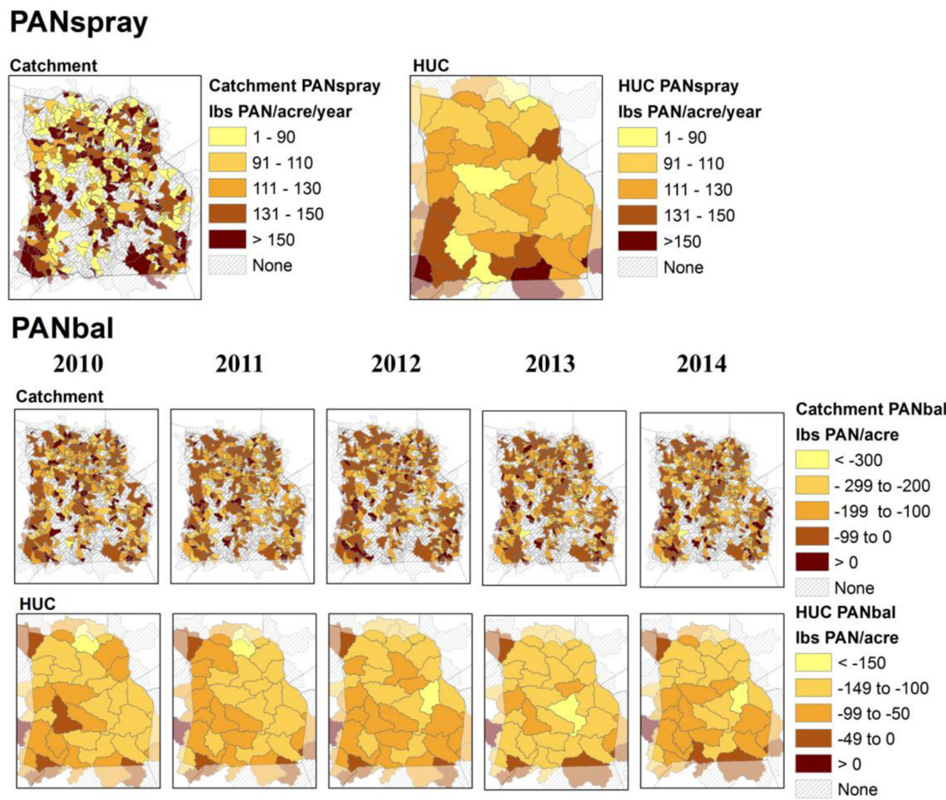

Figure 3.

Catchment and HUC12 sub-watershed pounds PANspray applied per sprayfield acreage and pounds PANbal per sprayfield acreage change over years 2010–2014 using remote sensing to determine PANcrops.

Table 1

Descriptive information regarding CAFO characteristics at different spatial scales based on location of CAFO point. All data are based on permitted data for Duplin County except calculated sprayfield acreage which was calculated in ArcGIS 10.2 using delineated sprayfield data.

	CAFO	SUB-WATERSHED		DUPLIN COUNTY
	Average per CAFO n=485	**Average per catchment n=510**	**Average per HUC12 n=34**	**Total**
CAFOs	1	2	15	485
Swine	4,639	4,364	68,176	2,249,824
Reported sprayfield acres	51	n/a	n/a	24,528
Calculated sprayfield acres	59	56	846	28,774
Accumulated manure (gallons/year)	4,030,884	3,780,485	59,243,187	1,955,025,172
PANspray (lbs/year)	6,838	6,506	97,568	3,316,441
PANcrops (lbs/year)	11,332	10,780	161,586	5,495,810
PANbal (lbs/year)	−4,494	−4,274	−64,017	−2,179,369

Table 2

The number and percent of catchments with sprayfields (n=510) having probability of PANbal>0 as reported in nutrient management plans (NMPs) and as calculated using remote sensing cropland data layer (CDL) 2010–2014

Probability PANbal>0	NMP		2010 CDL		2011 CDL		2012 CDL		2013 CDL		2014 CDL	
	n	%	n	%	n	%	n	%	n	%	n	%
>0.5	11	2%	72	14%	44	9%	55	11%	45	9%	54	11%
0.4–0.49	9	2%	8	2%	8	2%	17	3%	8	2%	8	2%
0.3–0.39	11	2%	16	3%	21	4%	15	3%	17	3%	19	4%
0.2–0.29	16	3%	18	4%	21	4%	22	4%	20	4%	22	4%
0.1–0.19	83	16%	42	8%	34	7%	53	10%	32	6%	25	5%
< 0.1	380	75%	354	69%	382	75%	348	68%	388	76%	382	75%