

Industrial Swine and Poultry Production Causes Chronic Nutrient and Fecal Microbial Stream Pollution

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Abstract Concentrated animal feeding operations (CAFOs) are the principal means of livestock production in the USA and Europe, and these industrial-scale facilities have a high potential to pollute nearby waterways. Chemical and biological stream water quality of a swine and poultry CAFO-rich watershed was investigated on 10 dates during 2013. Geometric mean fecal coliform counts were in the thousands at five of seven sites, especially in locations near swine waste sprayfields. Nitrate concentrations were very high and widespread throughout the watershed, with some individual samples yielding >10 mg-N/L. Ammonium concentrations were likewise high, but greatest near swine waste sprayfields, ranging up to 38 mg-N/L. Five-day biochemical oxygen demand (BOD₅) concentrations exceeded 10 mg/L in 11 of 70 stream samples, reaching as high as 88 mg/L. BOD₅ concentrations were significantly correlated with components of animal waste including total organic carbon, ammonium, and phosphorus, as well as the nutrient response variable chlorophyll *a*. The degree of nutrient and fecal contamination did not significantly differ between rainy and dry periods, indicating that surface and groundwater pollution occurs independently of stormwater runoff. This research shows that industrial-scale swine and poultry production leads to chronic pollution that is both a human health and ecosystem hazard. There are approx-

imately 450,000 CAFOs currently operating in the USA, with the majority located in watersheds feeding major riverine and estuarine systems with known water quality problems. Current US waste management protocols for this widespread system of livestock production fail to protect freshwater and estuarine ecosystems along the US Mid-Atlantic, Southeast and Gulf coasts, and expansion into industrializing nations will likely bring severe pollution with it.

Keywords CAFO · Nutrients · Fecal bacteria · BOD · Algal blooms

1 Introduction

Industrial-scale livestock production is the most common and widespread means of swine and poultry production in the USA and Europe (Thu and Durrenberger 1998; Thorne 2007) and occurs within facilities known as concentrated, or confined, animal feeding operations (CAFOs). The USEPA (2014) defines large CAFOs as containing ≥1000 head of beef cattle, 2500 swine >25 kg, 10,000 swine <25 kg, 125,000 chickens, 82,000 laying hens, or 55,000 turkeys. Large-scale production of livestock in CAFOs involves shipping in vast quantities of feed from elsewhere (often from other states) which results in the deposition of large amounts of excretory nitrogen, phosphorus, organic matter, and fecal microbes in the watershed where the CAFO is located (Cahoon et al. 1999; Mallin and Cahoon 2003). Waste generated by swine in CAFOs is hosed

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through slats in the floor of confinement buildings and is drained or pumped outdoors into a cesspit which the industry calls a “lagoon.” Periodically, the liquid waste supernatant of lagoons is pumped out and sprayed onto surrounding fields (i.e., sprayfields), which are planted with a cover crop such as Bermuda grass to absorb excess nutrients. Poultry waste is usually collected as dry litter, mixed with straw, and spread on neighboring fields; some CAFOs containing laying hens use the lagoon system. However, the production of vast quantities of animal manure within watersheds can overload the ecosystem’s capacity to dilute and process such waste (Carpenter et al. 1998; Weldon and Hornbuckle 2006). According to the USEPA (2014), there are approximately 450,000 CAFOs in the USA, unevenly distributed with the vast majority concentrated in a few states. While inventory and sales vary year to year, the largest swine-producing states include Iowa, North Carolina, Minnesota, Illinois, and Nebraska; the largest broiler chicken producers include Arkansas, Alabama, Mississippi, North Carolina, and Texas; and the largest turkey producers include North Carolina, Arkansas, Minnesota, Missouri, and South Carolina (USDA 2014a). This investigation did not include cattle CAFOs; however, cattle production is especially large in Texas, Nebraska, Kansas, Oklahoma, Iowa, Mississippi, and Wisconsin (USDA 2014a). The CAFO system has currently expanded beyond the USA and northern Europe into Eastern Europe and South America (Thorne 2007).

Serious human health (Cole et al. 2000; Wing and Wolf 2000) and environmental impacts (Campagnolo et al. 2002; Burkholder et al. 2007) of industrial animal production have been documented by researchers, including water quality impacts. The acute polluting impacts of large-scale accidents and hurricanes involving CAFO waste on freshwater streams and estuaries have been well documented (Burkholder et al. 1997; Mallin 2000; Mallin et al. 1999). The location of many CAFOs on river and stream floodplains renders receiving water vulnerable to such accidents, especially during major storms (Wing et al. 2002). CAFOs have been cited as supplying excessive nitrate to Midwestern streams in Ohio and Iowa (Weldon and Hornbuckle 2006; Hoorman et al. 2008). Karr et al. (2001) were able to trace nitrogen that was derived from CAFOs several kilometers downstream using isotopic techniques. A broad-scale study found that streams whose watersheds contained swine and poultry CAFOs had significantly

higher concentrations of ammonium, nitrate, and total N than streams whose watersheds lacked CAFOs (Harden 2015). Additionally, the deposition of manure and urine in storage lagoons and on surrounding fields has caused ammonium and/or nitrate pollution of groundwater on or near production facilities (Ritter and Chirnside 1990; Westerman et al. 1995; Liebhardt et al. 1979).

However, chronic pollution of surface waters by a suite of potential pollutants has not been comprehensively assessed for a CAFO-rich watershed. This research investigated physical, chemical, and biological pollution of stream waters in a watershed containing numerous swine and poultry CAFOs while lacking industrial or municipal point sources of pollution and containing little traditional crop agriculture. The degree of pollution was determined from two perspectives: first, since this stream consists of public waters, it was of interest to investigate whether or not these waters were impaired based on state chemical and biological standards. Second, comparative water quality conditions based on parameter concentrations were made using the published literature on coastal plain streams as well as broad-scale literature analyses of streams in general.

Stocking Head Creek (Fig. 1) is a second-order blackwater stream located in the Northeast Cape Fear River basin in eastern North Carolina. Catchment area is 1980 ha (4893 acres), and stream length to where it enters the Northeast Cape Fear River is 22.1 km (13.7 mi). The watershed soils are dominated by Noboco loamy fine sand, Johns fine sandy loam, Autryville loamy fine sand, Pactolus fine sand, Lumbee sandy loam, and Marvyn and Gritney soils (NRCS 2014a). There is some traditional row crop agriculture within this watershed, but aerial photography indicates that coverage by such is small in comparison to CAFO sprayfields and forest cover. The Northeast Cape Fear River is a fifth-order tributary of the sixth-order Cape Fear River, the watershed of which contains approximately half of the 9,000,000 plus swine in North Carolina as well as vast numbers of confined poultry. Cahoon et al. (1999) estimated that the Cape Fear River basin annually received 82,700 metric tons of nitrogen and 26,000 metric tons of phosphorus as animal waste in this watershed from CAFOs alone. Thus, CAFO-rich subwatersheds are likely to be sources of considerable nutrient pollution to larger rivers and estuaries (Mallin and Cahoon 2003; Burkholder et al. 2007). As such, our primary objective was to investigate potential environmental impacts to a stream draining a swine and poultry

CAFO-rich watershed. From July to October 2013, we sampled four main channels and three tributary stations for a broad selection of physical, chemical, and biological water quality parameters.

The location of swine CAFOs and the permitted numbers of swine for each are available from the North Carolina Department of Environment and Natural Resources, and we used these data to map and enumerate swine CAFOs. However, the N.C. Department of Agriculture and Consumer Services (NCDA & CS) does not provide such watershed-specific information on poultry CAFOs to the public or other agencies, although counts of each type of livestock are available on a county-by-county basis from NCDA & CS. Thus, a second objective was to obtain the locations of poultry CAFOs within this basin and estimate poultry numbers confined within them using alternative GIS and aerial photography-based techniques.

2 Methods

2.1 Sample Locations and Frequency

Seven stations were sampled, four on the main stream and two on first-order tributaries (Table 1, Fig. 1). The seventh station (MC-50) was collected on second-order Maxwell Creek, which joins lower Stocking Head Creek before it enters the Northeast Cape Fear River. The Maxwell Creek watershed also contains CAFOs, but they are not as concentrated near stream waters as those in the Stocking Head Creek watershed and they are not quantified in this investigation; MC-50 is used as a comparison site herein. All sites were sampled from bridges on public right-of-ways. The sampling design included five sample trips each taken during two different 30-day periods, one in mid-summer and one in fall. This was planned in accordance with the North Carolina Department of Environment and Natural Resources (NCDENR)'s protocol for fecal coliform sampling for assessment of whether a given stream supported its designated use or if it belongs on the state's 303(d) list for impaired waters. Sampling of Stocking Head Creek occurred during both dry and wet periods. Rainfall data were obtained from the NC CRONOS data set, using Station #319026 Wallace, latitude 34.72, longitude 77.97778, in Duplin County. Rainfall amount was computed for the day of sampling, the day of sampling plus

the previous 24-h period, and the day of sampling plus the previous 48-h period.

2.2 Sample Parameters and Methodology

To obtain a full perspective of the stream's physical and chemical qualities, a suite of parameters was sampled. Field measurements were made on-site using YSI field meters calibrated and checked according to standard procedures for water temperature, pH, dissolved oxygen, turbidity, and specific conductance. Samples were collected from surface waters by bucket haul and distributed into pre-cleaned bottles for nutrient (ammonium, nitrate, total nitrogen, orthophosphate, total phosphorus), total suspended solids (TSS), chlorophyll *a*, and 5-day biochemical oxygen demand (BOD5) analyses. Samples were kept on ice and delivered to the laboratory for subsequent analysis within proper holding times. Chain of custody records was maintained.

Analytical methods used (see APHA 1995; USEPA 1983, 1997) were as follows: TSS, SM 2540D; ammonium, EPA 350.1; nitrate+nitrite, EPA 353.2; TKN, EPA 351.2, total nitrogen as calculation of TKN+nitrate; orthophosphate, SM 4500PE; total phosphorous, SM 4500 PE; BOD5, SM 5210B; and fecal coliform bacteria, SM 9222D MF. Total organic carbon concentrations (TOC) were obtained during the fall sampling in an effort to better understand causes of high BOD5 levels that were seen in the summer; the analytical method used for TOC was SM 5310B. Chlorophyll *a* measurements were performed using EPA method 445.0, based on the Welschmeyer (1994) fluorometry method.

2.3 Statistical Analyses

Summary statistics were derived for each parameter (means, standard deviations, medians, minimum, maximum for all data, also geometric means for fecal coliform analysis). Data were tested for normality using the Shapiro-Wilk test, with most chemical and biological parameters requiring log-transformation prior to further statistical analysis. An important consideration was whether or not the pollutant concentrations measured in Stocking Head Creek were the result of acute stormwater-driven surface runoff into the creek or a result of chronic, long-term pollution impacting groundwater as well as surface waters. As such, we analyzed whether or not rainfall produced higher pollutant

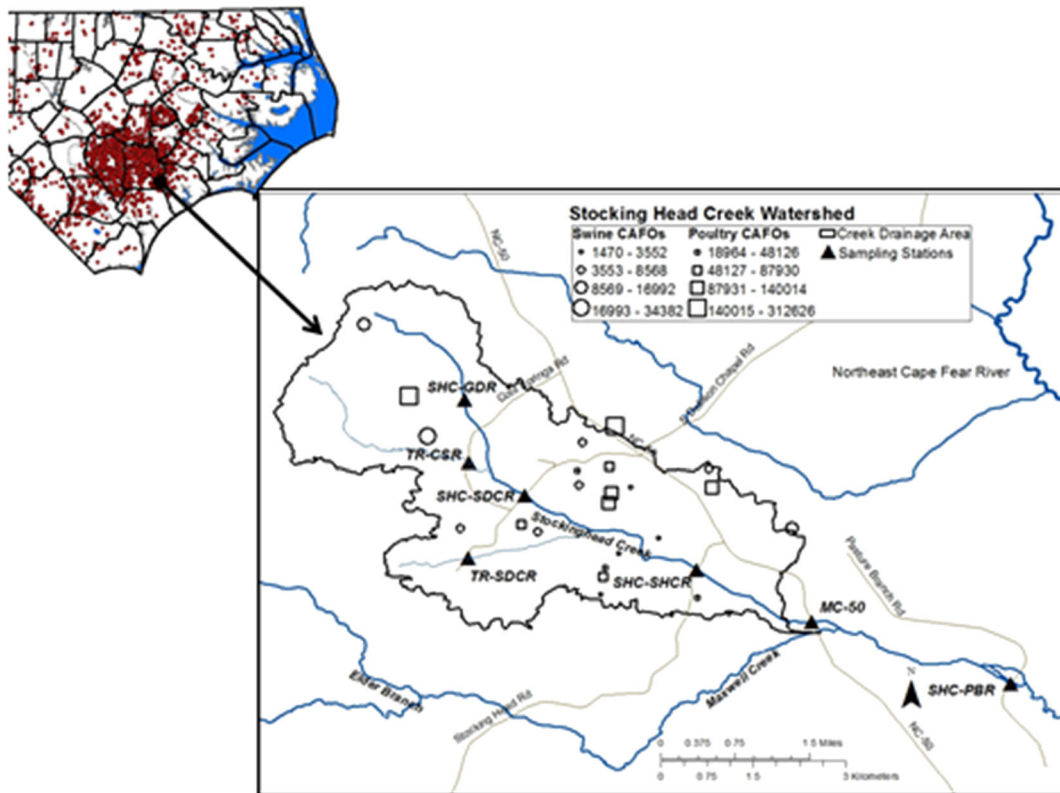


Fig. 1 Map of the Stocking Head Creek watershed, eastern North Carolina, USA, including streams, roads, sampling sites, and swine and poultry CAFOs sorted by size groups. *Inset* is the North Carolina Coastal Plain with *red dots* indicating location of swine CAFOs

parameter concentrations than occurred on non-rain periods. Measurable rainfall occurred either on the day of sampling or within the 48 h preceding the sample day on five of 10 sampling occasions. They were August 1 and 13, September 24, and October 8 and 10. *T* tests were used to test selected parameter concentrations between wet and dry periods ($\alpha=0.05$). Parameters tested for wet-dry differences included ammonium, nitrate, and fecal coliform bacterial concentrations. To assess potential chemical and biological parameters influencing BOD, correlation and regression analyses were performed using SAS (Schlotzhauer and Littell 1987).

2.4 CAFO Map Construction

A digital elevation model was downloaded from the USGS geospatial portal and used as the data input to delineate the watershed boundaries of Stocking Head Creek. The ArcMap 10.1 Hydrology toolset was utilized, and the catchment area of Stocking Head Creek system was identified. A shapefile including all of the

documented animal operations from the NC OneMap geospatial portal was clipped to only display those CAFOs within the newly defined watershed area. After establishing these boundaries and existing CAFOs (primarily swine operations), 2012 orthophotography from the North Carolina OneMap service was analyzed for undocumented CAFOs. The signature shape of the farm buildings (long rectangles side by side) was used to identify these locations, which were presumed to be poultry CAFOs. These were manually digitized as polygons superimposed on the aerial photos, and added to the existing CAFO location data to provide a more accurate assessment of the total number of animal operations within the Stocking Head Creek watershed. Besides the lack of inclusion on the NCDENR database, other characteristics that distinguish North Carolina poultry from swine CAFOs from the air include a lack of waste lagoons for poultry (all swine CAFOs contain waste lagoons but few poultry CAFOs do—egg-laying facilities only). Also, based on aerial photography, poultry CAFO structures are generally longer than swine

Table 1 Description and location of sampled sites, roughly in descending order from headwaters downstream in Stocking Head Creek. See Fig. 1 for locations, nearby roads, and CAFOs

<p>SHC-GDR (Stocking Head Creek at Graham Dobson Road): N 34.91197, W 77.94507. This location collects the uppermost branch of Stocking Head Creek; a swine CAFO and sprayfields are present several hundred of meters upstream from the sampling site. Aerial photos indicate that this stream initiates in what is now a swine CAFO sprayfield.</p>
<p>TR-CSR (unnamed first-order tributary at Cool Springs Road): N 34.90279, W 77.94440. This site had no immediately adjoining CAFOs or sprayfields, but the GIS map (Fig. 1) indicates a large swine CAFO and a large poultry CAFO upstream.</p>
<p>TR-SDCR (unnamed first-order tributary entering Stocking Head Creek at South Dobson Chapel Road): N 34.88878, W 77.94453. Grazing cattle were occasionally present upstream within 75 m of this site, and waste spraying equipment was stationed within 50 m upstream on several sampling dates.</p>
<p>SHC-SDCR (Stocking Head Creek at South Dobson Chapel Rd.): N 34.89796, W 77.93628. Numerous CAFOs, sprayfields, and grazing cattle were located within 200 m of the stream at this site.</p>
<p>SHC-SHCR (Stocking Head Creek at Stocking Head Road): N 34.88710, W 77.91124. A large CAFO sprayfield was located within 50 m of the stream, with a ditch carrying sprayfield runoff that emptied directly into the stream at this location.</p>
<p>MC-50 (Maxwell Creek at SR 50): N 34.87950, W 77.89438. This sampling site adjoined a wetland area which was hydrologically connected to Stocking Head Creek. The Maxwell Creek watershed also contains CAFOs, although fewer than those in Stocking Head Creek watershed (Fig. 1).</p>
<p>SHC-PBR (Stocking Head Creek at Pasture Branch Road): N 34.87043, W 77.86539. This location was the farthest downstream site sampled. This downstream area also likely receives inputs from CAFOs in the Maxwell Creek drainage. There was also an adjoining forested wetland that supplied flow to the stream here.</p>

CAFOs and have the feeding silo located at the building midpoint, while swine CAFOs have feeding silos located at the building's end.

The dimensions of each poultry building were computed from the digitized aerial photographs. Maximum bird (considered as broiler chickens) populations per building were estimated by assuming 743 cm² (0.80 ft²) of space allotted per bird as is standard for a major poultry producer (Sanderson Farms 2007). The United Egg Producers (2010) recommend 436–557 cm² (0.47 to 0.60 ft²) of space per egg-laying chicken; thus, we feel our counts are conservative. As there is no way to distinguish chicken from turkey operations from the air, for the purposes of this study, we assumed all broiler chickens. As a comparative reference regarding

livestock manure production, the National Resources Conservation Service within the US Department of Agriculture uses animal units, i.e., 1 cow=9 hogs=455 broiler chickens=67 turkeys (NRCS 2014b).

3 Results

The Stocking Head Creek watershed (excluding Maxwell Creek) contains 13 swine CAFOs that are permitted by NCDENR for collectively 108,068 heads of swine. This watershed also contains 11 poultry CAFOs, consisting of a total of 42 individual buildings. Average poultry house size was approximately 2323 m² (25,000 ft²), with an average capacity of 31,250 birds. Thus, the watershed can house a maximum of 1,312,500 broiler chickens or equivalent turkeys using the animal unit conversions above. Grazing cattle were visibly present in this watershed (with some photographed grazing directly under swine waste sprays), but an accurate count is beyond the capability of this study. Confined swine, poultry, and cattle produce large quantities of manure; conversion factors of excreted waste into total nitrogen, phosphorus, and fecal bacteria for these three livestock types can be found in Mallin and Cahoon (2003). While the local human population relies on septic systems for sewage treatment, aerial photography revealed only 67 human dwellings in the watershed, yielding a scant 0.03 septic systems/ha.

Summer water temperatures ranged between 22.0 and 28.0 °C, and fall water temperatures ranged from 16.1 to 22.6 °C. Most sampling events reflected neutral stream pH conditions ranging from 6.5 to 7.3. Dissolved oxygen concentrations ranged from mildly hypoxic (3.5 mg/L) to supersaturation (17.0 mg/L) during an algal bloom. Average turbidity by station ranged from 1.1 to 21.0 NTU (nephelometric turbidity units). Total suspended solids (TSS) in most cases were less than 25 mg/L (Table 2). Elevated TSS concentrations occurred a few times primarily at the tributary station TR-SDCR.

Ammonium in Stocking Head Creek during the 10 sample trips ranged from the detection limit (0.05 mg/L) to 37.8 mg/L (Table 2). Highest ammonium concentrations were found at station TR-SDCR, followed by station SHC-SHCR. These stations are both within 50 m of swine CAFO sprayfields (Table 1, Fig. 1). Nitrate concentrations in Stocking Head Creek were very high (Table 2). Whereas the highest ammonium

Table 2 Water quality parameter concentrations in Stocking Head Creek, 2013, given as mean±standard deviation/median/range; fecal coliforms as geometric mean/range. $n=70$, except for TOC where $n=35$

Parameter	Station						
	TR-SDCR	SHC-GDR	TR-CSR	SHC-SDCR	SHC-SHCR	MC-50	SHC-PBR
Turbidity	25.6±20.1	4.5±2.2	11.4±9.2	9.5±5.4	12.4±5.8	1.0±2.3	4.0±2.5
NTU	21.0	4.1	9.5	10.0	12.0	1.1	3.8
	4.0–72.0	2.0–10.0	1.0–31.0	2.0–22.1	6.3–22.0	0.0–8.0	1.0–8.0
TSS	23.9±18.2	5.6±2.4	15.0±28.3	9.5±3.6	10.9±4.4	3.2±1.6	4.2±3.5
mg/L	21.3	5.4	6.4	9.9	11.3	3.4	3.4
	5.8–56.7	3.3–10.8	1.4–94.0	2.9–14.9	5.2–19.0	1.4–6.1	1.3–12.1
DO	7.4±4.0	5.9±0.8	7.2±0.5	7.9±0.8	7.4±0.3	6.0±0.9	6.4±0.8
mg/L	5.8	5.8	6.9	7.7	7.4	5.9	6.1
	3.5–17.0	4.7–7.3	6.8–8.4	7.0–9.3	6.9–7.9	5.0–7.7	5.6–7.9
Ammonium	10.5±13.6	0.1±0.1	0.3±0.2	0.2±0.2	3.3±4.1	0.1±0.1	0.4±0.5
mg-N/L	3.6	0.1	0.2	0.1	1.0	0.1	0.1
	0.2–37.8	0.1–0.2	0.1–0.7	0.1–0.8	0.2–10.9	0.1–0.1	0.1–1.6
Nitrate	2.9±3.6	6.8±4.2	7.9±2.2	3.6±2.2	6.1±2.1	0.3±0.2	1.3±0.6
mg-N/L	1.4	6.0	8.4	3.9	6.3	0.2	1.1
	0.1–10.0	1.6–13.6	3.0–10.5	0.6–7.4	1.1–8.4	0.1–0.7	0.8–2.4
TN	15.7±16.7	7.2±4.2	8.4±1.8	3.9±2.2	8.7±4.1	0.5±0.3	1.8±0.9
mg-N/L	7.6	6.2	8.6	4.2	7.9	0.5	1.6
	0.5–46.6	2.1–13.6	4.3–10.8	0.8–7.4	2.1–16.1	0.1–0.9	0.8–3.5
OP	1.8±1.7	0.1±0.0	0.1±0.1	0.2±0.1	0.4±0.2	0.3±0.1	0.3±0.1
mg-P/L	1.6	0.1	0.1	0.2	0.3	0.3	0.3
	0.1–5.5	0.1–0.2	0.1–0.4	0.1–0.3	0.2–0.6	0.2–0.4	0.2–0.4
TP	2.8±8.3	0.2±0.1	0.2±0.2	0.2±0.1	0.5±0.2	0.3±0.1	0.4±0.1
mg-P/L	1.7	0.2	0.1	0.2	0.4	0.3	0.4
	0.2–10.7	0.1–0.3	0.1–0.6	0.1–0.3	0.3–0.8	0.2–0.4	0.3–0.6
TOC	36.1±13.9	14.2±1.2	10.9±0.9	13.7±1.6	19.0±3.9	17.5±1.4	16.2±0.8
mg-C/L	39.9	13.5	11.2	13.0	17.4	18.1	15.7
	13.1–50.4	13.2–15.5	9.6–11.9	12.5–16.3	14.3–23.1	15.1–18.4	15.5–17.4
Chlorophyll <i>a</i>	12.3±11.8	10.1±8.4	2.9±2.1	5.2±2.8	10.7±11.9	6.1±8.2	1.2±0.6
µg/L	8.5	8.0	2.0	5.0	7.0	2.0	1.0
	1.0–40.0	2.0–28.0	1.0–8.0	1.0–12.0	3.0–44.0	1.0–25.0	0.0–2.0
BOD ₅	18.7±25.7	2.0±1.2	1.7±0.8	2.7±3.5	7.4±8.3	3.2±6.3	1.4±0.5
mg/L	11.0	1.5	1.5	1.0	3.5	1.0	1.0
	1.0–88.0	1.0–4.0	1.0–3.0	1.0–12.0	1.0–25.0	1.0–21.0	1.1–2.0
Fecal col.	9126	1184	1470	1772	5863	220	391
CFU/100 mL	455–60,000	330–3000	546–5000	728–8000	1182–60,000	91–1360	55–4000

concentrations were found at the two sites located closest to waste sprayfields, several sites showed high nitrate, including sites distant from sprayfields (Table 2; Fig. 1). Concentrations ranged from 0.08 to 13.60 mg-N/L, with station means ranging from 0.30 to 7.94 mg-

N/L. Particularly high nitrate concentrations were documented at these four sites: SHC-GDR, TR-CSR, SHC-SDCR, and SHC-SHCR. On 12 of 70 sampling occasions, stream nitrate concentrations exceeded 8 mg-N/L. Total nitrogen (TN) concentrations ranged

from 0.11 to 46.70 mg-N/L, while highest individual station average TN concentrations occurred at TR-SDCR, TR-CSR, and SHC-SHCR. The TN values in this stream were dominated by inorganic nitrogen (i.e., nitrate and ammonium) rather than organic nitrogen, with average percent inorganic N ranging from 80 to 100 % of TN, depending upon station.

Orthophosphate concentrations in Stocking Head Creek ranged from 0.04 to 5.45 mg-P/L, with station means ranging from 0.11 to 1.78 mg-P/L (Table 2). Highest concentrations were found at station TR-SDCR, followed by SHC-SHCR. Total phosphorus ranged from 0.040 to 10.70 mg-P/L, and station means ranged from 0.15 at SHC-GDR to 2.83 mg-P/L at TR-SDCR, with SHC-SHCR second highest at 0.50 mg-P/L (Table 2). Most TOC concentrations were in the 10–20 mg/L range; however, higher TOC concentrations occurred at TR-SDCR and SHC-SHCR, the stations nearest to sprayfields (Table 2).

Chlorophyll *a* represents the amount of suspended live microalgal biomass found in a sample of water (Wetzel 2001). Elevated chlorophyll *a* concentrations (algal blooms) occurred at TR-SDCR on July 29 (40 µg/L) and at this same site on September 18 (44 µg/L), with smaller blooms occurring several times at other sites. Thus, algal blooms occurred within Stocking Head Creek, but were inconsistent in time and among sampling sites (Table 2).

Biochemical oxygen demand (BOD) is a measure of the organic matter available for consumption by the bacteria in a body of water during respiration; excessive BOD can lead to hypoxia. Five-day BOD (BOD₅) varied widely (Table 2), from background concentrations of 1.0 mg/L up to high values of 21 mg/L at MC-50, 25 mg/L at SHC-SHCR, and the maximum of 88 mg/L at station TR-SDCR. That station maintained the highest overall BOD₅ concentrations (Table 2), reaching 10 mg/L or more on six of 10 dates, while station SHC-SHCR exceeded 10 mg/L on three dates. The stream stations with highest average BOD concentrations were those in closest proximity to swine waste sprayfields (Table 1; Fig. 1).

North Carolina uses fecal coliform bacteria counts as a proxy for potentially pathogenic bacteria in fresh water bodies; this standard is commonly used throughout the southeast of the USA (EPA Region 4) for freshwater contact. The NC protocol (NCDENR 1999) for sampling and the means for determining fecal impairment of

a water body state that fecal coliform counts shall not exceed a geometric mean of 200 CFU/100 mL based on at least five consecutive samples during any 30-day period nor exceed 400 CFU/100 mL in more than 20 % of the samples examined during such period. Fecal coliform counts for Stocking Head Creek were generally very high (Fig. 2). During summer 2013, the upper five stations exceeded 400 CFU/100 ml on 100 % of the time sampled, and the geometric means for all seven stations exceeded 200 CFU/10 mL for five samples in 30 days. Fecal coliform counts for Stocking Head Creek in fall 2013 were even higher than those in summer; the upper five stations exceeded 400 CFU/100 ml on 96 % of the time sampled, and the geometric means for six of the seven stations exceeded 200 CFU/10 mL for five samples in 30 days. During both the summer and the fall sampling periods, fecal coliform criteria for impaired waters were well exceeded. Elevated fecal coliform counts occurred during both wet and dry periods. Highest fecal coliform counts occurred at TR-SDCR and SHC-SHCR, the stations nearest to sprayfields. Most other stations also had high counts, with geometric means exceeding 1000 CFU/100 mL (Table 2, Fig. 2). While lower Maxwell Creek (MC-50) maintained the lowest counts, it still exceeded state criteria for impaired waters.

An important consideration is whether or not the high pollutant values measured in Stocking Head Creek were the result of acute stormwater-driven surface runoff into the creek or a result of chronic, long-term pollution impacting groundwater as well as surface waters. As such, we analyzed whether or not rainfall produced higher pollutant parameter concentrations than occurred

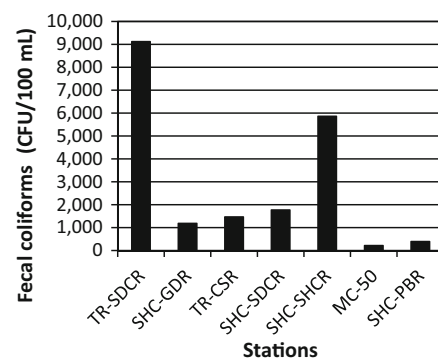


Fig. 2 Fecal coliform bacteria counts (as colony-forming units/100 mL) for Stocking Head Creek watershed sampling sites, presented as geometric mean of 10 samples per site. Note that the NC freshwater recreational standard is 200 CFU/100 mL

on non-rain periods. For all non-rain sample dates and stations, the fecal coliform geometric mean was 1455 CFU/100 mL, and counts exceeded 200 CFU/100 mL on 31 of 35 samples with 89 % exceedence of the state standard. For all rain periods and stations combined, the fecal coliform geometric mean was 1467 CFU/100 mL, and counts exceeded 200 CFU/10 mL on 30 of 35 samples with 86 % exceedence of the state standard. *T* test results showed no significant difference in means between wet and dry periods ($p=0.49$; $df=68$). Thus, fecal coliform pollution of Stocking Head Creek was not rain dependent; rather, fecal coliform pollution was a *chronic* condition.

Ammonium concentrations during non-rain periods were 2.67 ± 7.59 mg-N/L (mean \pm standard deviation) vs. rain period concentrations of 1.56 ± 4.65 mg-N/L. *T* test results on log-transformed data showed no significant difference in means ($p=0.64$; $df=68$). Nitrate concentrations during non-rain periods were 4.45 ± 3.68 mg-N/L vs. rain concentrations of 3.82 ± 3.56 mg-N/L. *T* test on log-transformed nitrate data showed no significant difference in means ($p=0.38$, $df=68$). Thus, inorganic nitrogen concentrations were not increased by rainfall-driven surface runoff, but instead they were a chronic condition in Stocking Head Creek, indicating ground-water pollution.

4 Discussion

Ammonium is a reduced form of inorganic nitrogen that is a major component of fresh human sewage or animal excreta (Clark et al. 1977). It is readily used by algae and bacteria, and an overabundance of ammonium can stimulate eutrophication (Wetzel 2001). Research in coastal plain blackwater streams and rivers has indicated that ammonium concentrations of 0.5 mg/L (ppm) or higher can stimulate algal blooms (Mallin et al. 2004). Additionally, ammonium exerts a significant chemical oxygen demand in sewage treatment plant discharges (Clark et al. 1977), as it is oxidized to nitrate. Thus, excess ammonium can lead to aquatic ecosystem deterioration through more than one pathway. The ammonium concentrations found in Stocking Head Creek, particularly at the sites nearest to sprayfields, greatly exceeded ammonium concentrations typically found in other coastal plain streams and rivers (Smock and Gilinsky 1992; Mallin et al. 2004, 2006). Previously, only during swine or poultry lagoon breaches have such concentrations

been found in receiving streams in this region (Burkholder et al. 1997; Mallin 2000).

Ammonium pollution from CAFOs is not limited to runoff or seepage entering waterways. Volatilization of ammonia from CAFOs releases vast amounts of inorganic nitrogen to the atmosphere. On the North Carolina Coastal Plain alone, annual ammonia emissions from swine and poultry have been estimated as 73,500 and 22,900 metric tons (Costanza et al. 2008). Regionally, ammonia volatilization from waste lagoons, sprayfields, and litterfields carries ammonia well outside of the watershed of origination (Walker et al. 2000; Costanza et al. 2008) and is reflected in elevated ammonium concentrations in rainfall measurements downwind (Willey et al. 2006). In a study of the two most CAFO-rich North Carolina watersheds, ammonium concentrations were found to have increased approximately 500 % in the Neuse River and 315 % in the Northeast Cape Fear River between 1995 and 2005 (Burkholder et al. 2006).

Ammonium at the concentrations found in Stocking Head Creek can have other impacts besides increasing algal blooms and chemical oxygen demand. Recent studies (see review by Glibert et al. 2015) have indicated that ammonium at these concentrations can stimulate cyanobacterial production as well as increase the production of toxic microcystin, while suppressing growth of diatoms which are generally benign organisms that support the higher trophic levels. Ammonium has been found to preferentially enhance cyanobacterial growth in locales as diverse as San Francisco Bay (Glibert et al. 2014) to the South Carolina Coastal Plain (Siegel et al. 2011). Interestingly, in July 2011, an unprecedented (during 23 years of monitoring) bloom of cyanobacteria (mostly *Anabaena planctonica*) occurred in the blackwater Northeast Cape Fear River downstream from its confluence with Stocking Head Creek (and several other CAFO-impacted watersheds). The bloom lasted for several weeks and, upon decomposition, resulted in a BOD that decreased river DO from 5.3 to 0.7 mg/L (S. Petter Garrett, NCDENR, personal communication August 4, 2011).

Nitrate is likewise readily used by visible plants and algae for growth. It is mobile in soils and readily moves through the water table to enter streams (Keeney 1986). Average nitrate concentrations at six of seven stations well exceeded levels known to stimulate algal production and lead to elevated BOD in blackwater streams (Mallin et al. 2004). Nitrate concentrations in this stream

were well in excess of those reported from other streams in the southeast USA (Edwards and Meyer 1987; Smock and Gilinsky 1992; Mallin et al. 2004, 2006; Carey et al. 2007), but in line with nitrate concentrations reported from Ohio watersheds impacted by runoff from combined row crop and dense CAFO presence (Hoorman et al. 2008). Regarding human health, there is a US EPA drinking well nitrate standard of 10 mg-N/L to prevent blue baby syndrome (also called methemoglobinemia). It is notable that on three occasions, even the 10-mg/L standard for drinking well water was exceeded, and in seven of 70 samples collected, stream nitrate concentrations exceeded 9 mg/L, close to the methemoglobinemia standard.

There are no point-source discharges entering this creek. The local human population uses septic systems, but the 67 human dwellings in the watershed are spaced well away from the creek, with sprayfields located between human dwellings and riparian areas. Thus, the principal sources of nitrate are swine CAFO waste (either runoff from sprayfields, or subsurface movement into the stream), poultry litter spread on fields, and cattle manure deposited on land. Nitrate concentrations of similar magnitude have been documented from subsurface waters draining sprayfields and surface streams passing through or near swine sprayfields (Evans et al. 1984; Stone et al. 1995). Total nitrogen concentrations in Stocking Head Creek were very high compared to available data from other blackwater coastal plain streams (Smock and Gilinsky 1992; Mallin et al. 2004, 2006). To provide a wider perspective, using a large data set of 1070 streams, Dodds et al. (1998) determined that average TN concentrations >1.5 mg/L were characteristic of eutrophic conditions; this level was well exceeded according to average station TN at six of the seven sites (Table 2).

Orthophosphate is the most common form of inorganic phosphorus directly used by algae. It is not very mobile in soils and adsorbs readily to soil particles (Wetzel 2001). Orthophosphate station means were generally 2–10 times the average levels found in a selection of less-impacted blackwater coastal plain streams (Edwards and Meyer 1987; Mallin et al. 2004, 2006; Carey et al. 2007). Average orthophosphate concentrations in Stocking Head Creek were similar to those in streams draining mixed row crop and CAFO watersheds in Ohio (Hoorman et al. 2008).

Concentrations of TP \geq 0.50 mg-P/L or greater can increase BOD in blackwater streams by serving as a

substrate assimilated by ambient bacteria (Mallin et al. 2004). In the present study, TP was higher than 0.50 mg-P/L in 11 of 70 samples. Using data from 1366 streams, Dodds et al. (1998) concluded that TP concentrations >0.075 mg/L were characteristic of eutrophic streams; average TP at all sites exceeded this threshold (Table 2). Additionally, a study of soils in eastern North Carolina using a soil phosphorus index developed by the N.C. Division of Agronomy found that the soils in counties where CAFOs were abundant (including Duplin County) contained excessively high index values (Cahoon and Ensign 2004). We note that besides direct eutrophication impacts, highly variable nutrient ratios (such as seen with this impacted stream) can lead to changes in taxonomic structure for resident phytoplankton and higher trophic levels (Glibert et al. 2015).

Bacteria require phosphorus both structurally and energetically (Kirchman 1994), and fecal bacteria growth in stream sediments can be stimulated by inputs of phosphate (Toothman et al. 2009). Also, fecal coliform bacteria within the water column can be significantly stimulated by additions of organic or inorganic P inputs >0.100 mg/L, increasing survival and reproduction (Chudoba et al. 2013). Mean and median concentrations of TP in all Stocking Head Creek stations exceeded 0.100 mg-P/L. The data suggest that high phosphorus inputs to stream waters polluted by fecal bacteria can magnify human health risks, as well as ecosystem impacts.

BOD5 concentrations at times were very high in Stocking Head Creek (Table 2). Comparison of BOD5 from many streams and rivers in coastal North Carolina indicates that concentrations of 1 to 2 mg/L are background for minimally impacted streams (Mallin et al. 2006). Elevated BOD can be stimulated by several causes. One common cause of elevated BOD is the introduction of organic materials such as human sewage or animal waste into the water; thus, dissolved organic carbon, if labile, can stimulate BOD (Clark et al. 1977). Another cause is algal blooms, which upon death and decay create a source of labile organic matter available for bacterial consumption. In a variety of coastal plain freshwater streams, tidal creeks, and lakes, Mallin et al. (2006) found strong statistical correlations between BOD and chlorophyll *a*. Ammonium pollution can exert a significant chemical oxygen demand in waterways, and elevated phosphorus concentrations can lead to elevated BOD by directly stimulating bacteria growth. In Stocking Head Creek, BOD5 was positively

correlated with TOC ($r=0.833$, $p<0.0001$), ammonium ($r=0.666$, $p<0.0001$), TP ($r=0.626$, $p<0.0001$), orthophosphate ($r=0.569$, $p<0.0001$), chlorophyll *a* ($r=0.316$, $p=0.008$), and TN ($r=0.284$, $p=0.017$). Multiple regression analyses indicated that the best predictive linear model for BOD₅ in this stream was (as log-transformed data)

$$\begin{aligned} \text{BOD}_5 &= 0.952(\text{TOC}) + 0.367(\text{AMM}) - 3.961, r^2 \\ &= 0.85, p < 0.0001 \end{aligned}$$

Thus, the high BOD in Stocking Head Creek is directly related to common components of animal waste (TOC, ammonium, phosphorus) as well as to chlorophyll *a*, a response variable to nutrient inputs. As mentioned, the lower Cape Fear River and its estuary are on the 303(d) list due to DO violations. Stocking Head Creek enters the Northeast Cape Fear River, which enters the lower Cape Fear River at Wilmington. The high levels of BOD observed in Stocking Head Creek as well as the high nitrate, ammonium, and fecal bacteria loads contribute to the low DO concentrations frequently occurring in summer in the Northeast Cape Fear River.

Most troublesome from a human health perspective is the data indicating that Stocking Head Creek is highly polluted by fecal bacteria, by both measures of the NC criteria for impaired waters. The upper five stations exceeded 400 CFU/100 ml on 96–100 % of the time sampled, and six of seven stations exceeded a geometric mean of 200 CFU/10 mL for five samples in both 30-day periods. Importantly, elevated fecal coliform counts occurred during both wet and dry periods; this creek is chronically polluted by fecal bacteria. The stimulatory effect of phosphorus loading on fecal bacteria (Chudoba et al. 2013) further exacerbates the potential human health issues. Fecal bacteria generated by livestock within the watershed are not confined to the immediate watershed but are likely to be carried downstream into higher order streams. A bacterial source-tracking study using molecular techniques demonstrated swine waste contamination at Cape Fear River system sites well downstream from swine CAFOs (Arfken et al. 2013).

In addition to surface waters, groundwater under and near swine and poultry CAFOs can contain very high inorganic nitrogen concentrations. Ritter and Chimside (1990) found ammonium concentrations up to 960 mg-N/L and nitrate up to 50 mg-N/L in test wells in close proximity to swine waste lagoons on the Delmarva

Peninsula. In North Carolina, Westerman et al. (1995) analyzed seepage from two swine waste lagoons and found ammonium concentrations in nearby wells averaged more than 50 mg-N/L, with nitrate of 6–15 mg-N/L. In other areas, it has also been observed that both spreading and spraying of livestock waste on the landscape will lead to excessive nitrate in groundwater (Liebhardt et al. 1979).

The water table in this area varies seasonally but is relatively near the land surface on average. No groundwater level monitoring wells are immediately on-site, but the US Geological Survey operates a well 10 km southwest at Rose Hill (Well DU-157). At that well, annual average depth to the surficial water table from 2004 to 2014 ranged from 1.3 to 2.7 m, with an average of 2.2 m. The North Carolina Division of Water Resources operates a monitoring well 10 km southeast at Chinquapin (Well W29D9), and 2013 data showed depth to surficial water table ranging from 1.4 to 1.8 m below the land surface. The local predominating sandy loam soils (NRCS 2014a) have moderate to rapid permeability with permeability rates of 0.5–1.5 m/day and 1.5–3.0 m/day, respectively (USDA 2014b). Thus, following a swine waste spray event, nitrate (and likely some portion of the fecal bacteria load) could migrate into the water table in as little as a day or two and from there move laterally to the nearest stream. Thus, groundwater in a CAFO-rich watershed such as that of Stocking Head Creek is a source of nitrogen and fecal bacterial pollution to the stream waters, and continual (including non-storm event) groundwater inputs into the stream at selected locations results in chronic pollution. Simply considering overland runoff will underestimate the N flux to aquatic systems as this ignores infiltration and leaching (Carpenter et al. 1998). The lack of concentration differences in fecal coliform, ammonium, and nitrate concentrations between rainy and dry periods shows that the stream pollution is chronic and a result of normal CAFO operations and presently accepted waste disposal techniques.

This research has demonstrated that drainage basins rich in CAFOs cause chronic pollution that has both human health and ecosystem impacts. However, the scope of US confined animal operations is nationwide. Many CAFO-rich watersheds pollute freshwater streams and rivers, which eventually enter estuaries located on the Atlantic and Gulf coasts. For instance, poultry CAFO-rich Delaware, Maryland, and Virginia, and poultry and swine CAFO-rich North Carolina drain

into middle-Atlantic estuaries. Major swine, poultry, and cattle-producing states such as Arkansas, Alabama, Iowa, Illinois, Minnesota, Missouri, and Texas in the Mississippi River drainage feed the Gulf of Mexico. As such, Weldon and Hornbuckle (2006) determined that for four major agricultural watersheds in Iowa, nitrate was strongly correlated with CAFO densities, and these watersheds made an outsized contribution to nitrate loading to the Mississippi River.

An extensive study covering 90 % of estuarine surface area in the USA (Bricker et al. 1999) concluded that severe eutrophication conditions (toxic algal blooms, bottom-water hypoxia, losses of submersed aquatic vegetation) were most prevalent along the middle Atlantic and Gulf Coast estuaries. Howarth et al. (2012) have demonstrated that estuarine nitrogen discharge from a wide selection of rivers in Europe and North America is positively correlated with net watershed nitrogen inputs. That study showed that for watersheds that have positive increases in animal feed from outside the system, there is a strong correlation with riverine N flux. Many of those rivers drain watersheds rich in poultry CAFOs, swine CAFOs, or both. The magnitude of industrial livestock production indicates that not only are immediate watersheds severely polluted but the collective impacts of the numerous subwatersheds draining CAFO-rich areas contribute to major ecosystem impacts far downstream as well. As the magnitude of the CAFO style of industrial livestock production grows beyond the USA and Europe into developing nations (Thorne 2007), highly concentrated nutrient and fecal microbial pollution from these sources will similarly expand.

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