

Ammonia Emissions from Broiler Operations Higher than Previously Thought



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This report was researched and written by Abel Russ and Eric Schaeffer of the Environmental Integrity Project.

THE ENVIRONMENTAL INTEGRITY PROJECT

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For questions about this report, please contact EIP Director of Communications Tom Pelton at (202) 888-2703 or tpelton@environmentalintegrity.org.

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Executive Summary

The Chesapeake Bay has long suffered from algae blooms, dead zones, and other effects on aquatic life that are caused by excess nitrogen and phosphorus pollution. The Total Maximum Daily Load (TMDL), often described as a “pollution diet” for the Bay, has resulted in significant pollution reductions, but further reductions will be necessary to restore the health of the Bay.

Ammonia, the pungent gas released from animal waste, is responsible for a significant fraction of the nitrogen load to the Chesapeake Bay each year. Airborne nitrogen is responsible for roughly one third of the nitrogen load. Historically, most of that nitrogen has been in the form of nitrogen oxides (NO_x) from fossil fuel combustion and other sources. Clean Air Act regulations have produced steady declines in NO_x, but ammonia has been increasing, and ammonia will soon be the dominant form of atmospheric nitrogen loads.

The largest source of ammonia emissions is livestock waste, and a large component of that source category comes from the factory farms that produce broiler chickens. Since ammonia from broilers is a significant pollution problem, we attempted to determine whether the Environmental Protection Agency was accurately estimating these emissions in its TMDL model. This report reaches the following conclusions:



A broiler chicken operation located on Maryland's Eastern Shore.

1. Broiler barns emit much more ammonia than EPA has traditionally assumed. The Chesapeake Bay model assumes that local broiler confinements emit the same amount of ammonia, per broiler, as similar facilities in Europe. Yet we know that American broiler emissions are much higher than European broiler emissions. This is due to a number of factors: We raise larger birds, and larger birds emit more

ammonia; we re-use the bedding (litter) in broiler confinements much more than European operations; and we raise our broilers in a warmer climate.

2. EPA has traditionally assumed that broilers emit 0.27 grams of ammonia per bird, per day. Based on our survey of the literature on American broiler operations, we believe that a more realistic estimate is 0.54 grams of ammonia per bird, per day.
3. Using alternative emissions factors, ammonia emissions are equal to 34.3 grams of ammonia per broiler sold, or 14.2 grams of ammonia for every kilogram of broiler sold.
4. Applying these factors to broiler statistics for the Bay states, we determined that actual ammonia emissions are roughly twice as high as what EPA assumes: EPA's emissions factor predicts emissions of roughly 20,000 tons per year, while our factors predict emissions of roughly 40,000 tons per year.
5. A typical broiler CAFO on the Delmarva Peninsula – producing 500,000 broilers each year at an average weight of six pounds – is likely emitting between 19 and 24 tons of ammonia each year. Yet EPA's emissions factor would only predict 12 tons.

In order to ensure that the EPA is accurately accounting for this important source of pollution, we urge EPA to clarify its assumptions about broiler confinement emissions, and if necessary adjust its assumptions to reflect the current state of the science with regard to American broiler operations.

Introduction

Ammonia emissions from factory farms present a clear threat to environmental quality. The prime example of this threat may be the Chesapeake Bay, where ammonia is a major contributor to persistent algae blooms and dead zones. According to the U.S. EPA's Total Maximum Daily Load (TMDL) for the Chesapeake Bay, “[a]ir sources contribute about a third of the total nitrogen loads delivered to the [] Bay.”¹ Specifically, using the models they had at the time, EPA estimated that atmospheric deposition was responsible for 31-36% of the total nitrogen load. Of that, the majority (78-81%) was deposited on land or non-tidal waterways and then transported to the Bay.²

Nitrogen deposits in various forms, mainly nitrogen oxides (NOx) and ammonia. Table 1 shows TMDL estimates of nitrogen deposition over time. Two things stand out. First, while NOx has historically been the dominant source of nitrogen deposition, ammonia is expected to be the dominant source now or in the near future. Second, while NOx deposition is falling over time, and wet ammonia deposition (ammonia that falls with precipitation) is

roughly constant, dry ammonia deposition (ammonia that deposits in gaseous form) is increasing.

Table 1. Atmospheric deposition loads of nitrogen (millions of pounds as N) to the Chesapeake Bay watershed. Adapted from TMDL Table L-3.³

| Year | Dry NO _x | Wet NO _x | Dry ammonia | Wet ammonia | Total N | Ammonia/total |
|------|---------------------|---------------------|-------------|-------------|---------|---------------|
| 1985 | 293 | 154 | 66 | 79 | 592 | 24% |
| 2002 | 208 | 102 | 66 | 76 | 452 | 31% |
| 2010 | 135 | 67 | 85 | 73 | 360 | 44% |
| 2020 | 97 | 50 | 98 | 76 | 321 | 54% |

The TMDL estimates in Table 1 suggest that ammonia deposition is currently responsible for roughly half of the atmospheric contribution, or roughly 17%, of the total nitrogen loads to the Bay.⁴

Why are ammonia emissions and deposition increasing?

Ammonia deposition is increasing for two reasons. First, changes in atmospheric chemistry, including a decline in atmospheric NO_x concentrations, increase the likelihood that ambient ammonia will deposit in gaseous form. Second, ammonia emissions are increasing, due mainly to an increase in animal production and a parallel increase in manure production.⁵

Ammonia is a highly reactive gas that tends to form fine particles by combining with NO_x and other gases in the air.⁶ As NO_x emissions fall, less ammonia is “captured” in fine particle formation. This is significant because gaseous ammonia has a short residence time in the atmosphere and deposits close to the source of emissions, while fine particles stay aloft for much longer and can travel far from the source.⁷ The steep decline in NO_x levels is a major victory for public health, helping to reduce smog and acid rain as well as the deadly fine particles linked to heart disease and premature death. NO_x is also contributing less to nitrogen loadings in the Bay as emissions decline. But those water quality benefits will be largely offset by increases in the local deposition of ammonia no longer reacting with NO_x to make fine particles.

The other factor causing an increase in ammonia deposition is the increase in ammonia emissions. Most of the ammonia in the air comes from agriculture. According to the most recent National Emissions Inventory, out of a national total of 3.9 million tons of ammonia that are emitted each year, 1 million tons come from synthetic fertilizer and 2.2 million tons come from livestock waste.⁸ When animal production increases, ammonia emissions also

increase. The Bay TMDL doesn't include any limits on ammonia emissions from agriculture, although EPA estimated emissions could be cut about 30% at fairly low cost.⁹ Instead, EPA is counting on the NOx reductions driven by Clean Air Act rules to keep the airborne nitrogen load low enough to meet cleanup goals by 2025. That scenario will be undermined if ammonia emissions prove to be higher than EPA expects.

Within the livestock sector, one of the largest sources of ammonia is the production of chickens for meat ("broilers"). On a per-weight basis, broilers excrete more nitrogen than any other major animal production group – more than twice as much as pigs, and more than three times as much as most cows.¹⁰

Since 2002, broiler production in the Chesapeake Bay watershed (in pounds) has increased by 25%, driven in part by a 17% increase in the average size of the broilers being sold (see Appendix A). As we show in more detail below, this has led to a large increase in ammonia emissions over the same time period.

Estimating Ammonia Emissions from Broiler Operations

Background

The amount of ammonia released from broiler confinements can be estimated in different ways. The most direct way is to simply measure the ammonia. This has been done in several studies, described below. For most broiler production facilities, however, routine monitoring is too expensive and technically challenging. It is therefore necessary to derive more generic emissions estimating methods that can be applied to facilities without monitors.

Methods for estimating emissions come with important trade-offs. The most accurate methods are complicated and data-intensive. Other methods are easier to use, but may be less accurate. The more complicated methods have to account for the long list of variables influencing emissions. To begin with, ammonia emissions from broiler CAFOs change over time. A typical broiler operation will raise multiple flocks of broilers each year. Older, heavier birds emit more ammonia than younger, smaller birds. This means that the emissions from a broiler house will increase as a flock of birds inside the house ages. After a flock is sold, the broiler house is cleaned out, either superficially ("decaking") or with a full removal of built-up manure and bedding. The cleanouts produce pulses of ammonia emissions that depend on, among other things, the number of flocks since the last full cleanout. Other factors affecting ammonia emissions include temperature and humidity.

These variables can be accounted for in emissions models, which can be either process-based or statistical. Process-based models attempt to estimate ammonia emissions using

basic physical and chemical principles and the input data described above. For example, researchers at Carnegie Mellon University have developed a model that predicts emissions based on the density of livestock in a barn, the nitrogen content of the waste, and ambient temperature.¹¹ Statistical models start with emissions monitoring data and attempt to predict emissions on the basis of a similar list of factors. The EPA draft Emissions Estimating Methodology (EEM) for broilers is an example of a set of statistical models.¹² In the draft EEM, EPA presented three models of increasing complexity that used between 11 and 31 regression coefficients, including average bird mass, confinement clean-out history, temperature, and humidity.¹³ Whether process-based or statistical, emissions models can only be used when all of the input variables can be quantified. This is often not possible. For example, we may want to estimate how much ammonia a planned, but not yet built, broiler CAFO will emit. We will know some things, like the number of chickens that the barns can hold, but we would only be guessing about variables like pounds of broilers produced each year, the schedule of barn cleanouts, and weather. Or we may be interested in aggregate emissions for a large, diverse area like the Chesapeake Bay watershed. Given the data and computational limitations at that scale, a complex emissions model may be too difficult to implement.

The simplest way to estimate emissions is to use an “emissions factor.” Emissions factors are basic coefficients, expressed (for broilers) as some variation on ‘pounds of ammonia per chicken.’ Emissions factors can be derived from monitoring data or models, but in either case they are meant to approximate an average facility. Emissions factors are less precise than detailed models, but on the other hand they are easier to use, and they can produce reasonably accurate emissions totals, particularly for large areas like states or the Bay watershed.

In the case of broiler confinements, emissions factors might have one of three denominators:

- **Inventory:** The EPA has traditionally used an inventory-based emissions factor, described in more detail below, in the form of kilograms of ammonia per broiler per year, or kilograms of ammonia per broiler per month, with broiler “inventory” being the average population of broilers in a confinement, or the capacity of broiler barns at a confinement. At the county or state level, inventory statistics can be found in the USDA Census of Agriculture, which is compiled every five years.¹⁴
- **Production (Sales):** It may be preferable to estimate emissions based on production rather than inventory. There can be several cycles or flocks of broiler production over the course of a year. For example, in 2012, Maryland had an average statewide broiler inventory of 64.2 million broilers, but it produced (sold) 304.7 million birds (Appendix A), suggesting that there were, on average, about five flocks of broilers at each confinement. In order to account for differences in the number of flocks per

year – differences that are not apparent in basic inventory statistics – ammonia emissions can be approximated as “pounds of ammonia per broiler sold.”¹⁵

- **Production (Weight):** Not all broilers are the same weight when they are sold. For example, the average broiler in Delaware weighs almost twice as much as the average broiler in West Virginia (see Appendix A). And we know that larger broilers excrete more ammonia. So a third emissions factor would be expressed as “pounds of ammonia per pound of broiler sold” over the course of a year.

In the discussion that follows we attempt to derive all three types of emissions factor from available monitoring studies.

EPA Emission Factors

The EPA has historically used an inventory-based emissions factor. Although the Agency has chosen to express the factor in different ways, the factor itself was constant from as early as 2004 through at least 2011.

In 2004, EPA published a draft report documenting the technical basis for its National Emissions Inventory (NEI). At that time, EPA expressed the ammonia emissions factor for broiler confinements as 0.22 pounds of ammonia per broiler per year (0.22 lb NH₃/head/yr).¹⁶ It is important to note that this emissions factor was derived entirely from European studies.¹⁷ American and European agricultural practices (and meteorological conditions) are quite different. European broiler operations tend to replace the litter after each flock, while American broiler operation reuse litter for up to a year.¹⁸ European operations generally grow lighter birds.¹⁹ Temperatures in Europe are cooler.²⁰ All of these factors cause American broiler emission rates to be significantly greater than European emission rates. Wheeler et al. (2006) presented seven American estimates alongside seven European estimates.²¹ The mean ammonia emissions rate from the American studies was 0.64 pounds per broiler per year, three times higher than the mean from the European studies (0.21 pounds per broiler per year).²²

In the documentation for the 2011 NEI, EPA stated that it was using Carnegie Mellon’s emissions model, but it listed a single emissions factor for broiler confinements.²³ The new emissions factor – 8.32E-03 kg NH₃/bird-month – is, after converting kilograms to pounds and months to years, equal to the old emissions factor. In the documentation for the 2014 NEI, EPA claims to have changed the way it uses the Carnegie Mellon model to estimate poultry emissions, but there is no evidence that the emissions factor for broiler confinements has changed.²⁴

For purposes of EPA’s Chesapeake Bay model, the Agency is using the 2011 NEI for at least part of its simulations,²⁵ and maybe for all of its simulations.²⁶ In short, it appears that

EPA continues to assume that broiler confinements emit 0.22 pounds of ammonia per broiler per year, an assumption based on outdated European data. As discussed in detail below, that assumption is probably far too low.

Monitored emissions from broiler houses: Total emissions

Ammonia emissions from broiler houses have been measured many times, in different locations (inside and outside the United States) and using different methods. We reviewed studies from within the United States in order to evaluate whether the current EPA emissions factor is still valid, and in order to approximate a more reasonable emissions factor. As a preliminary matter, it is important to note that some studies attempted to capture the full cycle of a broiler confinement, including the cleanout period that can cause a pulse in ammonia emissions, while other studies only looked at emissions while there were broilers in a barn. This section only looks at the studies that monitored the total emissions over full cycles, including the periods between flocks. The following section discusses studies that only looked at the grow-out period.

NATIONAL AIR EMISSIONS MONITORING STUDY (NAEMS)

Between 2007 and 2009, researchers working with the EPA monitored the emissions of ammonia and other pollutants from four broiler houses, two in California and two in Kentucky.²⁷ Ammonia emissions were calculated by subtracting ambient air concentrations from exhaust air concentrations. In 2012, EPA released a draft Emissions-Estimating Methodology (EEM) for broilers.²⁸ In that 2012 document, EPA provided the following simple summary statistics that include all periods (growout, decaking, and full cleanout):

Table 2: Summary ammonia data for NAEMS broiler studies.²⁹

| | Average house inventory | Average daily emissions (lb/d-house) | Grams per day per bird |
|-------------------|-------------------------|--------------------------------------|------------------------|
| California barn 1 | 21,000 | 22.49 | 0.49 |
| California barn 2 | 21,000 | 19.82 | 0.43 |
| Kentucky barn 1 | 23,000 | 26.76 | 0.53 |
| Kentucky barn 2 | 24,500 | 27.29 | 0.50 |

It is also possible to represent NAEMS emissions as a function of broiler production statistics. The Kentucky study derived a sales-based emissions factor of 35.4 grams of ammonia per bird marketed,³⁰ and a weight-based factor of 12.5 grams of ammonia per kilogram of broiler.³¹ The study of California barns did not provide comparable estimates, but the California study did provide daily data on bird counts and bird weight, from which

we can estimate production statistics. Appendix B provides an example of the data, and explains how we derived emissions factors from the data. Based on the raw data, it appears that production-based emissions factors for the California study would be 29 grams of ammonia per bird marketed, and 11 grams of ammonia per kilogram of broiler.

MOORE ET AL. (2011)

Moore et al. monitored four broiler barns in Arkansas in 2005 and 2006, over five flock cycles, including the periods between flocks.³² The authors present a production-based emissions estimate of 37.5 grams of ammonia per bird,³³ and they also provide average bird weight (2.582 kg), from which a weight-based estimate can be derived (14.5 grams of ammonia per kg of broiler). In order to translate these values into an inventory-based estimate, we had to make two calculations. First, since inventory generally refers to the number of birds placed in a barn, rather than the number that survive to be sold, and the broiler in this study had a mortality rate of roughly 4 percent, we had to convert 37.5 grams of ammonia per bird *sold* to 35.9 grams of ammonia per bird *placed*. Second, we had to determine how many days of emissions each bird was responsible for, including both the grow-out and the between-flock periods. The authors provide start dates for each of the five flocks in their study, from which we were able to calculate the lengths of the first four flock cycles (from one start date to the next).³⁴ The average flock cycle was 70.5 days. An inventory-based emissions factor would therefore be roughly 35.9 grams per bird divided by 70.5 days, or 0.51 grams of ammonia per bird per day.

Table 3: Summary of monitoring data and emissions factors for the full broiler cycle, including both grow-out and between-flock periods

| Source | Location | No. of barns | Average age of flock (days) | Average flock size (per barn) | Average market weight (kg) | g NH3/bird-day | g NH3/bird sold | g NH3/kg market weight |
|---------------------|----------|--------------|-----------------------------|-------------------------------|----------------------------|--------------------|--------------------|------------------------|
| EPA (2012) | CA | 2 | 47.0 ³⁵ | 21,000 ³⁶ | 2.65 ³⁷ | 0.46 ³⁸ | 29.0 ³⁹ | 11.0 ⁴⁰ |
| EPA (2012) | KY | 2 | 51.5 ⁴¹ | 25,100 ⁴² | 2.76 ⁴³ | 0.52 ⁴⁴ | 35.4 ⁴⁵ | 12.5 ⁴⁶ |
| Moore et al. (2011) | AR | 4 | 50.4 ⁴⁷ | 26,300 ⁴⁸ | 2.58 ⁴⁹ | 0.51 ⁵⁰ | 37.5 ⁵¹ | 14.5 ⁵² |

Monitored Emissions from Broiler Houses: Grow-Out Period Only

Several studies have measured ammonia emissions during the grow-out period only (i.e., not during the between-flock barn cleanouts). Lacey et al. (2003) measured ammonia emissions from four broiler houses in Texas in 2000, and derived an emissions factor of 31 grams of ammonia per bird.⁵³ Siefert et al. have published two studies on the Delmarva peninsula with quite different results. The first study, published in 2004, derived an emissions factor of 38 grams of ammonia per bird, while the second study, published in 2008, derived an emissions factor of just 5 grams of ammonia per bird. The authors attribute the difference in part to the fact that the newer study took place at a tunnel-ventilated broiler barn, while the earlier study took place at a side-wall ventilated house.⁵⁴ Yet all of the studies in Table 4, below, with the exception of the 2004 Siefert et al. study, were conducted at tunnel-ventilated houses, and all show much higher emissions rates. The 2008 Siefert and Scudlark study appears to be an outlier for some other reason, which may include errors in the analysis. Wheeler et al. (2006),⁵⁵ in a study funded by the U.S. Department of Agriculture, measured ammonia emissions from twelve barns in Pennsylvania and Kentucky in 2002 and 2003. The authors only assessed emissions during the grow-out period, but found a relatively wide range of daily emissions rates, from 0.47 to 0.98 grams of ammonia per bird per day. Miles et al. (2014) measured ammonia emissions from a single barn in Mississippi in 2007 over the course of five flocks.⁵⁶

Table 4: Summary of monitoring data and emissions factors for only the grow-out period

| Source | Location | No. of barns | Average age of flock (days) | Average flock size (per barn) | Average weight (kg) | g NH3/bird-day | g NH3/bird sold | g NH3/kg market weight |
|---|--------------------|--------------|-----------------------------|-------------------------------|----------------------|--------------------|--------------------|------------------------|
| Lacey et al. 2003 ⁵⁷ | TX | 4 | 49 | 27,500 | 2.4 | 0.63 ⁵⁸ | 31.0 | 12.9 ⁵⁹ |
| Siefert et al. 2004 ⁶⁰ | MD | 1 | 42 | 11,155 | <i>not available</i> | 0.90 ⁶¹ | 37.8 ⁶² | <i>not available</i> |
| Wheeler et al. 2006 ⁶³ | PA | 4 | 42 | 32,600 | 2.2 | 0.56 ⁶⁴ | 23.5 ⁶⁵ | 10.7 ⁶⁶ |
| Wheeler et al. 2006 ⁶⁷ | KY | 4 | 56 | 22,500 | 2.9 | 0.87 ⁶⁸ | 49.5 ⁶⁹ | 16.8 ⁷⁰ |
| Siefert and Scudlark 2008 ⁷¹ | Delmarva Peninsula | 1 | 42 | 18,600 | <i>not available</i> | 0.12 ⁷² | 5.2 ⁷³ | <i>not available</i> |
| Miles et al. 2014 ⁷⁴ | MS | 1 | 43 | 27,860 | 2.27 | 0.54 | 23.5 | 10.4 ⁷⁵ |

The studies that monitored total, full-cycle emissions (Table 3) also segregated emissions between the grow-out and between-flock periods, which allows us to derive scaling factors between grow-out emissions and total emissions. For production-based emissions factors, the scaling factor will be a multiplier that increases the emissions factor, because each broiler is responsible for between-flock emissions that are always additive to grow-out emissions. For an inventory-based emissions factor, the scaling factor could theoretically result in an increase or a decrease in the amount of ammonia emitted per bird per day. Although peak emissions during the clean-out or decaking of a barn will often be higher than peak emissions during the grow-out period, the average daily emission rate over the entire between-flock period may be lower than the average daily emission rate during the grow-out period. Tables 5 and 6 compare grow-out and total emissions from studies with available data. These tables show that total emissions are roughly 21% higher than emissions from the grow-out period only, and that the total daily emissions rate over the entire flock cycle is roughly 7% lower than the daily emissions rate during the grow-out period.

Table 5: Total emissions compared to emissions for the grow-out period

| Study | Grow-out emissions | Total emissions | Total emissions / grow-out emissions |
|--|-------------------------------|-------------------------------|--------------------------------------|
| Moore et al. (2011) ⁷⁶ | 28.37 g NH ₃ /bird | 37.46 g NH ₃ /bird | 1.32 |
| EPA (2012), California barns ⁷⁷ | 4,049.48 kg NH ₃ | 4,466.41 kg NH ₃ | 1.10 |
| EPA (2012), Kentucky barns ⁷⁸ | 3,619.62 kg NH ₃ | 4,373.08 kg NH ₃ | 1.21 |
| Average ratio (scaling factor) | | | 1.21 |

Table 6: Total emissions rates compared to emissions rates for the grow-out period

| Study | Grow-out emissions rate, g/bird-day | Total emissions rate, g/bird-day | Total emissions rate / grow-out emissions rate |
|--|-------------------------------------|----------------------------------|--|
| Moore et al. (2011) ⁷⁹ | 0.56 ⁸⁰ | 0.51 ⁸¹ | 0.91 |
| EPA (2012), California barns ⁸² | 0.50 ⁸³ | 0.46 ⁸⁴ | 0.92 |
| EPA (2012), Kentucky barns ⁸⁵ | 0.56 ⁸⁶ | 0.52 ⁸⁷ | 0.95 |
| Average ratio (scaling factor) | | | 0.93 |

Using the scaling factors shown in Tables 5 and 6, we combined the emissions estimates from Table 3 with adjusted emissions estimates from Table 4 to derive average emissions factors from all of the literature values. Table 7 shows this derivation.

Table 7: Combined emissions factors

| Study | Grams of ammonia per bird, per day | Grams of ammonia per bird marketed | Grams of ammonia per kg of market weight |
|---|------------------------------------|------------------------------------|--|
| EPA (2012), ⁸⁸ CA | 0.46 | 29.0 | 11.0 |
| EPA (2012), KY | 0.52 | 35.4 | 12.5 |
| Moore et al. (2011) ⁸⁹ | 0.51 | 37.5 | 14.5 |
| Lacey et al. (2003) ⁹⁰ | 0.59 | 37.5 | 15.6 |
| Siefert et al. (2004) ⁹¹ | 0.84 | 45.7 | <i>not available</i> |
| Wheeler et al. (2006), ⁹² PA | 0.52 | 28.4 | 13.0 |
| Wheeler et al. (2006), KY | 0.81 | 59.9 | 20.3 |
| Siefert and Scudlark (2008) ⁹³ | 0.11 | 6.3 | <i>not available</i> |
| Miles et al. (2014) ⁹⁴ | 0.50 | 28.4 | 12.6 |
| Average value | 0.54 | 34.3 | 14.2 |

Note: Highlighted cells are based on values in Table 4, but adjusted with the scaling factors shown in Tables 5 and 6.

The studies shown in Table 7 are mutually consistent, which increases the reliability of the combined estimates. Most studies predict daily emissions of between 0.4 and 0.6 grams of ammonia per bird. The lowest (0.11 grams per bird per day) and highest (0.84 grams per bird per day) estimates were both generated by Siefert et al., and do not change the overall average value. Similarly, total emissions are generally in the range of 30-60 grams of ammonia per bird, or 10-20 grams of ammonia per kilogram of broiler weight. In short, the range of estimates is generally within a factor of two, which is comparable to (or better) than the data used to develop emissions factors for most other industries.⁹⁵

Broiler Emissions in the Chesapeake Bay Watershed

Using the emissions factors derived in the preceding sections and the broiler statistics shown in Appendix A, we estimated the ammonia emissions from broiler confinements in the Chesapeake Bay states in 2002, 2007 and 2012 (all years for which broiler inventory data are available), and also 2016 (the most recent year with production statistics). Table 8

compares our estimates with emissions estimated using the most recent obtainable EPA method (the 2011 NEI method). It should be noted that the 2011 NEI method and our inventory-based emissions factor can be directly compared, as they both use broiler inventory statistics. The NEI method is equivalent to 0.27 grams of ammonia per bird, per day. Based on the monitoring data described above, EPA’s NEI factor is much too low, and the true factor should be roughly twice as large, at 0.54 grams of ammonia per bird, per day. Total emissions estimates presented in Table 8 reflect this difference.

Table 8: Ammonia emissions (tons) from broiler confinements in the Chesapeake Bay states using different emissions factors

| Year | 2011 NEI method | Emissions factors derived from monitoring data, as described above | | |
|------|---|--|---------------------------------------|---|
| | 8.32E-03 kg NH ₃ /bird-month | 0.54 g NH ₃ /bird-d | 34.3 g NH ₃ /bird marketed | 14.2 g NH ₃ /kg of market weight |
| 2002 | 19,370 | 38,239 | 38,944 | 37,460 |
| 2007 | 22,088 | 43,605 | 38,981 | 40,314 |
| 2012 | 20,888 | 41,237 | 38,339 | 40,861 |
| 2016 | | | 41,628 | 47,009 |

Table 8 shows that broiler confinements in the Chesapeake Bay watershed emit roughly 40,000 tons of ammonia each year, and that the amount is increasing over time. The three emissions factors that we derived produce roughly comparable results, within 5 or 10 percent of each other, for any given year. Table 8 also shows that the NEI emissions factor for broiler operations is outdated and too low, estimating half as much ammonia as the three factors that we derived.

Discussion

We estimate that broiler confinements in the Chesapeake Bay watershed emit roughly 40,000 tons of ammonia each year. For comparison, the 2014 NEI estimated that ammonia emissions from all livestock waste totaled 96,000 tons,⁹⁶ and EPA’s most recent estimate of ammonia *deposition* in the watershed is 81,000 tons.⁹⁷ Broilers are clearly a large part of the ammonia problem, and it is important that the Bay model get this part of the puzzle right. An outdated emissions factor based on European agricultural practices is not the right fit for today’s Chesapeake Bay.

It helps to frame these estimates in terms of a typical broiler CAFO. We have previously reported on data found in “Annual Implementation Reports” for broiler CAFOs on Maryland’s Eastern Shore.⁹⁸ Based on these reports, a typical Eastern Shore broiler CAFO

might have an inventory of 110,000 broilers and raise 4.8 flocks per year. If we assume 3% mortality,⁹⁹ this CAFO would produce 512,160 broilers per year, at an average weight of about 6 pounds (see Appendix A), thus producing just over 3 million pounds of broilers per year. According to the 2011 NEI emissions factor, this CAFO would emit 12 tons of ammonia per year. According to the emissions factors that we derived, this CAFO would actually emit between 19 and 24 tons of ammonia per year.

Our estimates are based on monitoring studies, but they agree well with mass-balance estimates of ammonia emissions. Coufal et al. (2006) measured all nitrogen inputs and outputs over eighteen flocks at a Texas broiler barn.¹⁰⁰ Overall, these authors determined that ammonia losses totaled 13.5 grams per kilogram of broiler weight,¹⁰¹ very close to our estimated emissions factor of 14.2 grams per kilogram (Table 7).

The use of litter amendments can help to reduce ammonia emissions to some degree. For example, in a doctoral dissertation on this topic, Senyondo found that small experimental broiler flocks treated with a biodegradable litter amendment made from corn cobs had ammonia emission that were, on average, 27% lower than control flocks.¹⁰² The effectiveness diminished over the course of five flocks as the litter was left in place, and by the fifth flock the treatment emissions were actually higher than the control emissions.¹⁰³ Another study evaluated the effectiveness of three alum treatments, and found that average weekly emissions were between 9 and 34% lower from alum-treated barns than from a control barn.¹⁰⁴

Some of the studies that we included in this report did not use litter amendments (e.g., the EPA NAEMS study), others included a mix of barns that did or did not use litter amendments (e.g., Wheeler et al., 2006),¹⁰⁵ and others did not specify whether amendments were used. If the use of litter amendments is more widespread in the Chesapeake Bay watershed than it was in the studies we evaluated, then actual emissions may be slightly lower than we predict. However, this variable does not significantly affect our conclusions: We do not know the extent of litter amendment in the Bay watershed, but even if its use is widespread, the resulting reduction in emissions is presumably less than a third (since at least some of the data in this report was based on amended litter). This means that even in a best-case scenario, emissions are still significantly higher than EPA has traditionally assumed.

Given the possibility that EPA is underestimating a significant component of the Chesapeake Bay's nitrogen load, the Agency should more clearly explain how much ammonia it assumes to be escaping from broiler confinements. If EPA is still relying on outdated emissions factors based on European agricultural practices, it should revise its assumptions to reflect what we now know about ammonia emissions from American broiler operations.

Appendix A: Broiler statistics for the Chesapeake Bay Watershed

Data for inventory and birds sold through 2012 are from the USDA Census of Agriculture, which is compiled every five years.¹⁰⁶ Data for pounds of broilers produced, and for birds sold in 2016, are from USDA Poultry Production and Value summaries, which are produced each year.¹⁰⁷

Table A1: Inventory and production of broiler chickens in Chesapeake Bay states

| Inventory (millions of birds) | MD | VA | PA | DE | WV | TOTAL |
|-------------------------------------|---------|---------|---------|---------|-------|---------|
| 2002 | 51.1 | 45.4 | 21.6 | 45.6 | 12.2 | 176.0 |
| 2007 | 65.5 | 43.7 | 27.5 | 51.1 | 12.8 | 200.7 |
| 2012 | 64.2 | 38.4 | 29.2 | 43.2 | 14.8 | 189.8 |
| | | | | | | |
| Production (millions of birds sold) | MD | VA | PA | DE | WV | TOTAL |
| 2002 | 287.1 | 266.1 | 132.5 | 255.9 | 88.7 | 1,030 |
| 2007 | 296.4 | 249.2 | 150.1 | 246.1 | 88.8 | 1,031 |
| 2012 | 304.7 | 237.7 | 166.7 | 211.6 | 93.7 | 1,014 |
| 2016 | 303.5 | 269.1 | 185.7 | 252.5 | 90.3 | 1,101 |
| | | | | | | |
| Production (millions of pounds) | MD | VA | PA | DE | WV | TOTAL |
| 2002 | 1,381.4 | 1,330.4 | 701.2 | 1,494.7 | 368.2 | 5,276 |
| 2007 | 1,591.9 | 1,301.0 | 831.6 | 1,597.7 | 355.6 | 5,678 |
| 2012 | 1,604.8 | 1,306.8 | 962.1 | 1,505.2 | 376.0 | 5,755 |
| 2016 | 1,851.4 | 1,533.9 | 1,039.9 | 1,843.3 | 352.2 | 6,621 |
| | | | | | | |
| Average bird size (lbs) | MD | VA | PA | DE | WV | AVERAGE |
| 2002 | 4.8 | 5.0 | 5.3 | 5.8 | 4.2 | 5.1 |
| 2007 | 5.4 | 5.2 | 5.5 | 6.5 | 4.0 | 5.5 |
| 2012 | 5.3 | 5.5 | 5.8 | 7.1 | 4.0 | 5.7 |
| 2016 | 6.1 | 5.7 | 5.6 | 7.3 | 3.9 | 6.0 |

Appendix B: Deriving production-based ammonia emissions factors from the California NAEMS study

The National Air Emissions Monitoring Study (NAEMS) included two broiler studies, one in California and one in Kentucky.¹⁰⁸ The Kentucky study authors provided summary estimates of ammonia emissions per bird marketed and bird kilogram of bird weight.¹⁰⁹ The California study did not provide comparable estimates, but did provide raw data from which these estimates can be derived. Figure B1, below, shows an example of the California data. At the end of a flock cycle, the inventory typically declines gradually and then drops off sharply; in Figure B1, house H10 had 20,463 birds on April 11-14, and then 2,558 on the next day (April 15). We assumed that the number of birds produced in each flock cycle was the last ‘large’ inventory number. In Figure B1, for example, we would assume that 20,463 birds were sold on April 14-15, each weighing an average of 2.69 kilograms.

Daily emissions estimates included both days with broilers in the barns (“grow-out” period), and days between flocks (“clean-out” or “decaking” period), but were only available for 60% of the 792-day study period. To estimate total emissions over all 792 days, we multiplied the average daily emissions estimate for each barn by the total number of study days, under the assumption that the days with emissions estimates were representative of the days without emissions estimates. With these assumptions in mind, Table B1 shows the calculation of production-based emissions estimates for the two California barns.

Figure B1: Sample animal characteristic data for California broiler barns in the NAEMS study.¹¹⁰

Table E2. Daily means of animal characteristics at Site CA1B for April, 2008.

| Day | House 10 | | | House 12 | | |
|-----|-----------|----------|--------------------|-----------|----------|--------------------|
| | Inventory | Mass, kg | kg m ⁻² | Inventory | Mass, kg | kg m ⁻² |
| 1 | 20,622 | 1.69 | 22.9 | 20,717 | 1.69 | 23.0 |
| 2 | 20,611 | 1.77 | 24.0 | 20,699 | 1.77 | 24.1 |
| 3 | 20,598 | 1.86 | 25.1 | 20,683 | 1.86 | 25.2 |
| 4 | 20,581 | 1.94 | 26.1 | 20,668 | 1.94 | 26.2 |
| 5 | 20,564 | 2.02 | 27.2 | 20,652 | 2.02 | 27.3 |
| 6 | 20,548 | 2.10 | 28.3 | 20,635 | 2.10 | 28.4 |
| 7 | 20,528 | 2.18 | 29.3 | 20,613 | 2.18 | 29.4 |
| 8 | 20,517 | 2.25 | 30.3 | 20,591 | 2.25 | 30.4 |
| 9 | 20,501 | 2.33 | 31.3 | 20,573 | 2.33 | 31.4 |
| 10 | 20,481 | 2.41 | 32.3 | 20,553 | 2.41 | 32.4 |
| 11 | 20,463 | 2.48 | 33.3 | 20,536 | 2.48 | 33.4 |
| 12 | 20,463 | 2.55 | 34.2 | 20,536 | 2.55 | 34.3 |
| 13 | 20,463 | 2.62 | 35.1 | 20,536 | 2.62 | 35.3 |
| 14 | 20,463 | 2.69 | 36.0 | 20,536 | 2.69 | 36.2 |
| 15 | 2,558 | | | 4,706 | | |
| 16 | 0 | | | 0 | | |
| 17 | 0 | | | 0 | | |
| 18 | 0 | | | 0 | | |
| 19 | 0 | | | 0 | | |
| 20 | 0 | | | 0 | | |
| 21 | 0 | | | 0 | | |
| 22 | 16,433 | 0.08 | 1.1 | 12,968 | | |
| 23 | 21,259 | 0.07 | 0.9 | 21,360 | 0.07 | 1.0 |
| 24 | 21,249 | 0.06 | 0.8 | 21,320 | 0.06 | 0.8 |
| 25 | 21,231 | 0.06 | 0.8 | 21,294 | 0.06 | 0.8 |
| 26 | 21,220 | 0.06 | 0.8 | 21,274 | 0.06 | 0.8 |
| 27 | 21,205 | 0.07 | 0.9 | 21,250 | 0.07 | 0.9 |
| 28 | 21,188 | 0.08 | 1.1 | 21,218 | 0.08 | 1.1 |
| 29 | 21,178 | 0.10 | 1.4 | 21,190 | 0.10 | 1.3 |
| 30 | 21,161 | 0.12 | 1.7 | 21,174 | 0.12 | 1.6 |
| Avg | 15,870 | 1.37 | 18.5 | 15,876 | 1.43 | 19.3 |
| n | 30 | 23 | 23 | 30 | 22 | 22 |
| SD | 8,604 | 1.07 | 14.3 | 8,546 | 1.05 | 14.2 |
| Min | 0 | 0.06 | 0.8 | 0 | 0.06 | 0.8 |
| Max | 21,259 | 2.69 | 36.0 | 21,360 | 2.69 | 36.2 |

Table B1: Calculating production-based ammonia emissions factors.

| H10 | | | | H12 | | | |
|----------------|----------------|---------------------------------------|-------------|----------------|----------------|---------------------------------------|-------------|
| Flock end date | birds produced | average bird mass, kg | kg produced | Flock end date | birds produced | average bird mass, kg | kg produced |
| 11/2/2007 | 20,516 | 2.48 | 50,880 | 11/2/2007 | 20,516 | 2.48 | 50,880 |
| 12/30/2007 | 20,705 | 2.62 | 54,247 | 1/1/2008 | 18,802 | 2.75 | 51,706 |
| 2/21/2008 | 19,631 | 2.61 | 51,237 | 2/20/2008 | 20,364 | 2.68 | 54,576 |
| 4/14/2008 | 20,463 | 2.69 | 55,045 | 4/14/2008 | 20,536 | 2.69 | 55,242 |
| 6/6/2008 | 18,952 | 2.63 | 49,844 | 6/5/2008 | 20,590 | 2.55 | 52,505 |
| 7/31/2008 | 19,822 | 2.75 | 54,511 | 7/31/2008 | 20,386 | 2.76 | 56,265 |
| 9/26/2008 | 20,799 | 2.68 | 55,741 | 9/26/2008 | 19,102 | 2.68 | 51,193 |
| 12/3/2008 | 20,951 | 2.56 | 53,635 | 12/3/2008 | 20,811 | 2.55 | 53,068 |
| 1/27/2009 | 20,625 | 2.68 | 55,275 | 1/27/2009 | 20,821 | 2.69 | 56,008 |
| 3/27/2009 | 20,514 | 2.68 | 54,978 | 3/26/2009 | 20,348 | 2.61 | 53,108 |
| 5/26/2009 | 20,165 | 2.68 | 54,042 | 5/26/2009 | 20,474 | 2.68 | 54,870 |
| 7/20/2009 | 20,055 | 2.62 | 52,544 | 7/20/2009 | 20,174 | 2.69 | 54,268 |
| 9/13/2009 | 18,662 | 2.61 | 48,708 | 9/13/2009 | 18,657 | 2.63 | 49,068 |
| TOTAL | 261,860 | | 690,686 | TOTAL | 261,581 | | 692,757 |
| | | total study days | 792 | | | total study days | 792 |
| | | average daily ammonia emissions (g/d) | 10,208 | | | average daily ammonia emissions (g/d) | 8,958 |
| | | g NH3 for the study period | 8,084,736 | | | g NH3 for the study period | 7,094,736 |
| | | g NH3/bird produced | 30.9 | | | g NH3/bird produced | 27.1 |
| | | g NH3/kg market weight | 11.7 | | | g NH3/kg market weight | 10.2 |

Note: Data were taken from the California study report.¹¹¹ “Birds produced” and “average bird mass” were assumed to be equal to the last day in a flock cycle with a large number of birds. Highlighted cells in the following table were calculated from the raw data.

Notes

¹ U.S. EPA, Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment, Appendix L, page L-2 (Dec. 29, 2010).

² Id.

³ Id. at page L-16, Table L-3.

⁴ The Bay watershed model does not present atmospheric deposition estimates for most of the watershed; instead, these are counted with the various land uses on which the nitrogen deposits. Jeff Sweeney at the Bay Program offered to extract the deposition numbers for us.

⁵ See, e.g., Y. Li et al., Increasing importance of deposition of reduced nitrogen in the United States, 113 PNAS 5874-5879 (May 24, 2016).

⁶ See, e.g., J.A. Koziel et al., Gas-to-particle conversion process between ammonia, acid gases, and fine particles in the atmosphere, *Agricultural and Biosystems Engineering Publications* 67 (2006), available at http://lib.dr.iastate.edu/abe_eng_pubs/67/?utm_source=lib.dr.iastate.edu%2Fabe_eng_pubs%2F67&utm_medium=PDF&utm_campaign=PDFCoverPages.

⁷ R.W. Pinder et al., Environmental impact of atmospheric NH₃ emissions under present and future conditions in the eastern United States, 35 *Geophysical Research Letters* L12808 (2008).

⁸ U.S. EPA, 2014 National Emissions Inventory (NEI) Data, <https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data> (accessed Nov. 7, 2016).

⁹ U.S. EPA, Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment, Appendix L, page L-14 (Dec. 29, 2010).

¹⁰ U.S. EPA, National Emission Inventory—Ammonia

Emissions from Animal Husbandry Operations, Draft Report, Table 3-7 (Jan. 30, 2004), https://www3.epa.gov/ttnchie1/ap42/ch09/related/nh3inventorydraft_jan2004.pdf

¹¹ Carnegie Mellon University, CMU Ammonia Emission Inventory for the Continental United States, <https://www.cmu.edu/ammonia/>; A.M. McQuilling and P.J. Adams, Semi-empirical process-based models for ammonia emissions from beef, swine, and poultry operations in the United State, 120 *Atmospheric Environ.* 127 (2015)

¹² U.S. EPA, Development of Emissions Estimating Methodologies for Broiler Operations (Draft) (Feb. 2012) (hereinafter “Draft EEM”).

¹³ Draft EEM at 7-1 and 7-49.

¹⁴ USDA Census of Agriculture, <https://www.agcensus.usda.gov/Publications/2012/>.

¹⁵ See, e.g., P. Moore et al., Ammonia Emissions Factors from Broiler Litter in Barns, in Storage, and after Land Application, 40 *J. Environ. Quality* 1395, 1398 (2011).

¹⁶ U.S. EPA, National emission inventory, ammonia emissions from animal agricultural operations (revised draft report), at 3-15, Table 3-8 (2004).

¹⁷ Id. at D-13, Table D-12.

¹⁸ D.M. Miles et al., Ammonia and Nitrous Oxide Emissions from a Commercial Broiler House, 43 *J Environ. Quality* 1119, 1120 (2014); E.F. Wheeler et al., Ammonia Emissions from Twelve U.S. Broiler Chicken Houses, 1511, 49 *Transactions of the ASABE* 1495, 1511 (2006).

¹⁹ E.F. Wheeler et al., Ammonia Emissions from Twelve U.S. Broiler Chicken Houses, 49 *Transactions of the ASABE* 1495, 1511 (2006).

²⁰ R.L. Siefert et al., Characterization of Atmospheric Ammonia Emissions from a Commercial Chicken House on the Delmarva Peninsula, 38 *Environ. Sci. Technol.* 2769, 2777 (2004).

²¹ E.F. Wheeler et al., Ammonia Emissions from Twelve U.S. Broiler Chicken Houses, 49 *Transactions of the ASABE* 1495, 1510 (2006).

- ²² Id. at 1510, Table 4, converted from g NH₃ b⁻¹ d⁻¹. The range of American values was 0.47-1.18 g NH₃ b⁻¹ d⁻¹, while the range of European values was 0.09-0.48 g NH₃ b⁻¹ d⁻¹.
- ²³ U.S. EPA, NEI technical documentation, 85, Table 3-33 (Aug. 2015), https://www.epa.gov/sites/production/files/2015-10/documents/nei2011v2_tsd_14aug2015.pdf. The report includes a link to county-specific emissions factors, but for broiler confinements all emissions factors were equal to 8.32E-03 kg NH₃/bird-month.
- ²⁴ U.S. EPA, 2014 National Emissions Inventory, version 1, Technical Support Document, 4-45 (Dec. 2016).
- ²⁵ U.S. EPA Chesapeake Bay Program, Atmospheric deposition of nitrogen in the Chesapeake: Integrating Air & Water Environmental Management, Chesapeake Bay TMDL 2017 Midpoint Assessment Webinar Series, slide 49 (Oct. 31, 2017), https://www.chesapeakebay.net/channel_files/25651/atmo_dep_webinar_draft_11-1-17.pdf.
- ²⁶ After repeated attempts, EPA staff were unable to answer this question.
- ²⁷ U.S. EPA, Development of Emissions Estimating Methodologies for Broiler Operations (Draft) (Feb. 2012) (hereinafter “Draft EEM”).
- ²⁸ Id.
- ²⁹ Id. at 4-10.
- ³⁰ Draft EEM, Appendix D, Final Project Report on Southeastern Broiler Gaseous and Particulate Matter Emissions Monitoring (Dec, 2009), page 5
- ³¹ Id. Calculated from 6.25 kg NH₃ per AU (defined on the same page as 500 kg of animal weight).
- ³² P. Moore et al., Ammonia Emissions Factors from Broiler Litter in Barns, in Storage, and after Land Application, 40 J. Environ. Quality 1395, 1398 (2011).
- ³³ Id. at 1404, Table 3; the authors present separate estimates for the grow-out (28.37 g NH₃/bird) and between-flock (9.09 g NH₃ per bird) periods, which can be combined for a total of 37.46 g NH₃ per bird).
- ³⁴ Id. at 1398, Table 1.
- ³⁵ Draft EEM, Table 5-8.
- ³⁶ Id. at Table 5-7.
- ³⁷ Id. at Table 5-7.
- ³⁸ See *supra*, Table 2.
- ³⁹ See *supra*, Table 3.
- ⁴⁰ See *supra*, Table 3.
- ⁴¹ Draft EEM, Table 5-8.
- ⁴² Id. at Table 5-7.
- ⁴³ Id. at Table 5-7.
- ⁴⁴ See *supra*, Table 2.
- ⁴⁵ Draft EEM, Appendix D, Final Project Report on Southeastern Broiler Gaseous and Particulate Matter Emissions Monitoring (Dec, 2009), page 5.
- ⁴⁶ Id. Calculated from 6.25 kg NH₃ per AU (defined on the same page as 500 kg of animal weight).
- ⁴⁷ P. Moore et al., Ammonia Emissions Factors from Broiler Litter in Barns, in Storage, and after Land Application, 40 J. Environ. Quality 1395, 1398, Table 1 (2011).
- ⁴⁸ Id.
- ⁴⁹ Id. at 1399.
- ⁵⁰ Id., derived as described in the text of this report.
- ⁵¹ Id. at 1404, Table 3.
- ⁵² Id., calculated as average emissions per bird (37.46 grams, page 1404) divided by average bird weight (2.582 kg, page 1399).

- ⁵³ R.E. Lacey et al., Particulate Matter and Ammonia Emission Factors for Tunnel-Ventilated Broiler Production Houses in the Southern U.S., 46 *Transactions of the ASAE* 1203 (2003).
- ⁵⁴ R.L. Siefert and J.R. Scudlark, Determination of ammonia emission rates from a tunnel ventilated chicken house using passive samplers and a Gaussian dispersion model, 59 *J Atmos. Chem.* 99, 109 (2008).
- ⁵⁵ E.F. Wheeler et al., Ammonia Emissions from Twelve U.S. Broiler Chicken Houses, 49 *Transactions of the ASABE* 1495 (2006).
- ⁵⁶ D.M. Miles et al., Ammonia and Nitrous Oxide Emissions from a Commercial Broiler House, 43 *J Environ. Quality* 1119, 1123 (2014).
- ⁵⁷ R.E. Lacey et al., Particulate Matter and Ammonia Emission Factors for Tunnel-Ventilated Broiler Production Houses in the Southern U.S., 46 *Transactions of the ASAE* 1203 (2003).
- ⁵⁸ Id., calculated as per-bird emissions divided by flock age.
- ⁵⁹ Id., calculated as per-bird emissions divided by average bird weight.
- ⁶⁰ R.L. Siefert et al., Characterization of Atmospheric Ammonia Emissions from a Commercial Chicken House on the Delmarva Peninsula, 38 *Environ. Sci. Technol.* 2769 (2004).
- ⁶¹ Id., converted from 0.74 grams of ammonia-nitrogen per bird per day (page 2777).
- ⁶² Id., daily per-bird emissions factor multiplied by flock age (42 days).
- ⁶³ E.F. Wheeler et al., Ammonia Emissions from Twelve U.S. Broiler Chicken Houses, 49 *Transactions of the ASABE* 1495 (2006).
- ⁶⁴ Average of 0.47 and 0.65 g NH₃ b⁻¹ d⁻¹ (Wheeler et al., Table 4).
- ⁶⁵ Id., calculated as daily per-bird emission rate multiplied by average age of flock.
- ⁶⁶ Id., calculated as per-bird emissions divided by average weight.
- ⁶⁷ E.F. Wheeler et al., Ammonia Emissions from Twelve U.S. Broiler Chicken Houses, 49 *Transactions of the ASABE* 1495 (2006).
- ⁶⁸ Average of 0.76 and 0.98 g NH₃ b⁻¹ d⁻¹ (Wheeler et al., Table 4).
- ⁶⁹ Id., calculated for each Kentucky farm as daily per-bird emission rate multiplied by average age of flock, then averaged for both Kentucky farms.
- ⁷⁰ Id., calculated for each Kentucky farm as per-bird emissions divided by average weight, then averaged for both Kentucky farms.
- ⁷¹ R.L. Siefert and J.R. Scudlark, Determination of ammonia emission rates from a tunnel ventilated chicken house using passive samplers and a Gaussian dispersion model, 59 *J Atmos. Chem.* 99 (2008).
- ⁷² Id. at 113, converted from ammonia-nitrogen to ammonia.
- ⁷³ Id., converted from ammonia-nitrogen to ammonia.
- ⁷⁴ D.M. Miles et al., Ammonia and Nitrous Oxide Emissions from a Commercial Broiler House, 43 *J Environ. Quality* 1119, 1123 (2014).
- ⁷⁵ Id., calculated as per-bird emissions divided by average weight.
- ⁷⁶ P. Moore et al., Ammonia Emissions Factors from Broiler Litter in Barns, in Storage, and after Land Application, 40 *J. Environ. Quality* 1395, 1404 (2011).
- ⁷⁷ Draft EEM at 5-14 – 5-16.
- ⁷⁸ Id.
- ⁷⁹ P. Moore et al., Ammonia Emissions Factors from Broiler Litter in Barns, in Storage, and after Land Application, 40 *J. Environ. Quality* 1395, 1404 (2011).
- ⁸⁰ Id., calculated as grow out emissions per bird (page 1404, Table 3) divided by average flock age of 50.4 days (page 1398, Table 1).
- ⁸¹ See section 3(a)(ii) of this report.
- ⁸² Draft EEM at 5-14 – 5-16.

- ⁸³ *Id.*, calculated as grow-out emissions rate (grams per day, Table 5-12) divided by inventory numbers (Table 4-3).
- ⁸⁴ See *supra*, Table 2.
- ⁸⁵ *Id.*
- ⁸⁶ Draft EEM, calculated as grow-out emissions rate (grams per day, Table 5-12) divided by inventory numbers (Table 4-3).
- ⁸⁷ See *supra*, Table 2.
- ⁸⁸ U.S. EPA, Development of Emissions Estimating Methodologies for Broiler Operations (Draft) (Feb. 2012).
- ⁸⁹ P. Moore et al., Ammonia Emissions Factors from Broiler Litter in Barns, in Storage, and after Land Application, 40 *J. Environ. Quality* 1395 (2011).
- ⁹⁰ R.E. Lacey et al., Particulate Matter and Ammonia Emission Factors for Tunnel-Ventilated Broiler Production Houses in the Southern U.S., 46 *Transactions of the ASAE* 1203 (2003).
- ⁹¹ R.L. Siefert et al., Characterization of Atmospheric Ammonia Emissions from a Commercial Chicken House on the Delmarva Peninsula, 38 *Environ. Sci. Technol.* 2769 (2004).
- ⁹² E.F. Wheeler et al., Ammonia Emissions from Twelve U.S. Broiler Chicken Houses, 49 *Transactions of the ASABE* 1495 (2006).
- ⁹³ R.L. Siefert and J.R. Scudlark, Determination of ammonia emission rates from a tunnel ventilated chicken house using passive samplers and a Gaussian dispersion model, 59 *J Atmos. Chem.* 99 (2008).
- ⁹⁴ D.M. Miles et al., Ammonia and Nitrous Oxide Emissions from a Commercial Broiler House, 43 *J Environ. Quality* 1119 (2014).
- ⁹⁵ See, e.g., U.S. EPA, Emission Factor Documentation for AP-42 Section 13.2.2, Unpaved Roads, Final Report, at 3-12 (Sep., 1998), available at <https://www3.epa.gov/ttnchie1/ap42/ch13/bgdocs/bl13s02-2.pdf> (“The level of variability within an emission factor data set is defined in terms of the spread of the original emission factor data values about the mean or median single-valued factor for the source category. The fairly rigorous criterion that all data points must lie within a factor of two of the central value was adopted”).
- ⁹⁶ U.S. EPA, 2014 National Emissions Inventory, <https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data> (total of ammonia emissions from livestock waste for Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and Washington, DC).
- ⁹⁷ U.S. EPA Chesapeake Bay Program, Chesapeake Bay Midpoint Assessment Progress, Tracking, Graphical interface to the Phase 6 Watershed Model Inputs: Atmospheric Deposition Data, Atmospheric Deposition Map, <https://mpa.chesapeakebay.net/AtmoDepData.html> (last accessed Dec. 7, 2017). Total reduced nitrogen deposition (66,787 tons) was converted to total ammonia deposition (81,208 tons).
- ⁹⁸ EIP, More Phosphorus, Less Monitoring (Sep. 8, 2015), available at http://www.environmentalintegrity.org/wp-content/uploads/2016/11/Poultry-report_2013.pdf.
- ⁹⁹ See, e.g., D.M. Miles et al., Ammonia and Nitrous Oxide Emissions from a Commercial Broiler House, 43 *J Environ. Quality* 1119, 1120 (2014) (2.6% mortality); R.L. Siefert et al., Characterization of Atmospheric Ammonia Emissions from a Commercial Chicken House on the Delmarva Peninsula, 38 *Environ. Sci. Technol.* 2769, 2772 (2004) (3% mortality).
- ¹⁰⁰ C.D. Coufal et al., *Nitrogen Emissions from Broilers Measured by Mass Balance Over Eighteen Consecutive Flocks*, 85 *Poultry Science* 384 (2006).
- ¹⁰¹ *Id.* at 388, converted from 11.07 grams of nitrogen per kilogram of broiler weight, using the authors’ assumption that virtually all gaseous nitrogen losses would be in the form of ammonia (*Id.* at 390).
- ¹⁰² N.S. Senyondo, Mitigation of Ammonia Emissions from Broiler Houses Using a Biodegradable Litter Amendment, Dissertation submitted to the faculty of Virginia Polytechnical Institute, 63, 81 (Apr. 3, 2013).
- ¹⁰³ *Id.*
- ¹⁰⁴ P.A. Moore et al., Evaluation of Ammonia Emissions from Broiler Litter, Livestock Environment VIII, Proceedings of the 31 August – 4 September 2008 Conference (Aug. 31, 2008). The authors state that average weekly emissions were reduced by 26-47%, but the data shown in Table 2 show actual reductions of 9-34%.

¹⁰⁵ E.F. Wheeler et al., Ammonia Emissions from Twelve U.S. Broiler Chicken Houses, 49 *Transactions of the ASABE* 1495, 1497 (2006). Broiler flocks with and without litter amendments were grouped together in this study, so the effects of amendments could not be ascertained.

¹⁰⁶ USDA Census of Agriculture, <https://www.agcensus.usda.gov/Publications/2012/>.

¹⁰⁷ USDA, Poultry Production and Value, <http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1130>.

¹⁰⁸ Draft EEM.

¹⁰⁹ Id. at Appendix D, Final Project Report on Southeastern Broiler Gaseous and Particulate Matter Emissions Monitoring (Dec, 2009), page 5.

¹¹⁰ Draft EEM, Appendix D, Emissions Data from two Broiler Chicken Houses in California, 76 (July 2, 2010).

¹¹¹ Id.



1000 Vermont Avenue, NW
Suite 1100
Washington, DC 20005
202-296-8800
www.environmentalintegrity.org