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ATMOSPHERIC POLLUTANTS AND TRACE GASES

Ammonia and Nitrous Oxide Emissions from Broiler Houses with Downtime Windrowed Litter

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Abstract

An emerging poultry manure management practice is in-house windrowing to disinfect the litter. However, this practice is likely to increase emissions of ammonia (NH_3) and nitrous oxide (N_2O) from the windrowed litter. The objective of this study was to quantitatively compare NH_3 and N_2O emissions from broiler houses with and without in-house windrowing. Two broiler houses at a commercial farm were used to compare the NH_3 and N_2O emissions. Gas emission measurements were conducted continuously and simultaneously for both the control house (without windrowing) and the house with windrowing during the same production periods. The house emission rates were calculated by multiplying the hourly mean gas concentrations and the ventilation rates. The windrowed litter temperature was significantly higher than that of the control litter. The impact of downtime (the time lapse between flocks, during which the bird house is empty) windrowing litter on pathogen reduction was inconclusive because of very low or no recovery of both *Escherichia coli* and *Salmonella* spp. from control or windrowed litter samples, respectively. The windrowing house NH_3 emissions were 26.2 and 16.6 kg d^{-1} $house^{-1}$, whereas for the control house, they were 14.6 and 12.8 kg d^{-1} $house^{-1}$ in 2012 and 2013, respectively. The N_2O emissions from the windrowing house were also higher than those from the control house. The total NH_3 and N_2O emissions from broiler houses practicing windrowing litter management were estimated to be 35.0 and 4.43 g $bird^{-1}$, respectively, compared with 31.9 and 3.89 g $bird^{-1}$ for the control house, respectively.

Core Ideas

- Significantly high NH_3 and N_2O emissions from a downtime windrowing house.
- 31% of NH_3 and 16% of N_2O emissions per bird were attributed to windrowing litter.

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Wood shavings or straw are commonly used as bedding materials for commercial broiler production. Due to high costs of replacing bedding after harvesting each flock, the litter is commonly reused for multiple flocks before its complete replacement with fresh bedding. After using the same litter for multiple flocks, the litter becomes built-up litter, a mixture of manure, litter, and waste feed. Pathogenic microorganisms such as *Salmonella*, *Escherichia coli*, *Clostridium*, *Campylobacter*, and others, which may be present in the built-up litter, can be transmitted to the next flock and cause an increase in bird mortality (Lavergne et al., 2006). In-house windrow composting is a popular treatment and disposal option for drying built-up litter, reducing pathogen and NH_3 loads. When biomass is composted, the core compost heats up to thermophilic temperatures of 50 to 65°C due to the biologically produced heat and the insulating effect of compost (Ro et al., 1998; Bernal et al., 2009). With the high temperature attained during composting, pathogenic microorganisms can be killed or significantly reduced. However, partial windrow composting of built-up litter during the 2-wk downtime between flocks technically does not produce a finished, stabilized compost because this short time is insufficient for conversion of the organic material in the litter into a humus-like material. Nevertheless, windrowing the built-up litter between flocks attains thermophilic temperatures, with the litter attaining temperatures >50°C for a few days before gradually cooling down to ambient temperature (Lavergne et al., 2006). Even with these relatively short thermophilic periods of windrowed litter, pathogenic bacterial populations can be significantly reduced in the litter. Therefore, partial windrow composting of built-up litter in a broiler house between flocks can reduce the likelihood of disease spread, such as dermatitis, and improve broiler meat production (Lavergne et al., 2006; Liang et al., 2010; Tabler et al., 2014). Although beneficial in reducing microbial load and improving broiler production efficiency, the high litter temperature attained from partial windrow composting may also increase fugitive gas emissions from the litter.

Ammonia is one fugitive gas emitted from livestock operations, which accounts for most of the NH_3 emissions in the United States. Ammonia is a principle source of atmospheric

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Abbreviations: FANS, Fan Assessment Numeration System; LTB, Lauryl Tryptose broth; MAC, MacConkey agar; MPN, most probable number; PGA, photoacoustic gas analyzer.

aerosols and contributes to regional acidification and eutrophication problems (Phillips, 1995; Doorn et al., 2002; Ro et al., 2008b). Ammonia emission from broiler housing consists of the emissions while birds are actively fed to market size in the house, as well as the emissions from an empty house during downtime between flocks, when the built-up litter remains in the house. Numerous reports have documented NH_3 emissions while the bird houses are populated with live birds (Wheeler et al., 2006; Burns et al., 2007; Gates et al., 2008; Moore et al., 2011; Miles et al., 2014). These studies reported that NH_3 emission rates increased in a linear or polynomial function with bird age (i.e., days in flock). In contrast, relatively limited information is available in the literature on NH_3 emissions from empty poultry houses between flocks. Topper et al. (2008) reported daily NH_3 emission rates of 13.4 and 15.3 kg d^{-1} $house^{-1}$ from two empty broiler houses between flocks. The built-up litter in these houses underwent conventional management, including caked litter removal, harrowing, and disking to prepare for next flock. Moore et al. (2011) reported intraflock NH_3 emissions of 339 ± 198 mg m^{-2} h^{-1}, which would be equivalent to 15.2 ± 8.9 kg d^{-1} using the poultry house dimension as a surface area. Burns et al. (2007) reported downtime NH_3 emission rates of 6.32 and 11.91 kg d^{-1} $house^{-1}$ from the broiler houses undergoing conventional litter management.

The NH_3 emission rate from a broiler house undergoing windrowing litter management during downtime was compared with that from a house with conventional litter management used as a control by Liang et al. (2010). A relatively high NH_3 emission rate (19.4 kg d^{-1} $house^{-1}$) from a litter windrowing house was observed. However, a higher NH_3 emission rate of 22.3 kg d^{-1} $house^{-1}$ was observed from the control house. The authors partially explained the decrease in surface area per unit volume of the windrowed litter as the reason for the higher NH_3 emission rate from the control house. It was noticed that the higher windrowed litter temperature would increase NH_3 volatilization rates. Interestingly, a much lower downtime NH_3 emission rate was observed from the windrowed litter (8.77 ± 8.27 kg d^{-1} $house^{-1}$) by the same authors (Liang et al., 2014). The authors attributed this lower NH_3 emission rate to lower litter moisture, less litter mass, or smaller floor area.

Greenhouse gas emissions, especially N_2O emissions from bird housing, are also of concern due to their very high global warming potential. Nitrous oxide can be formed both during nitrification and denitrification stages of biological NH_3 conversion to dinitrogen gas (Bremner and Blackmer, 1978; Ro et al., 2006; Brown et al., 2008; Ro et al., 2008a). Composting biomass provides both aerobic and anaerobic or denitrifying regions within the compost matrix (Ro et al., 1998). Therefore, the potential to produce N_2O by composting organic nitrogen-rich biomass such as animal manure is high. In fact, composting cattle manure generated high N_2O emissions without amendment (Hao et al., 2001). Although N_2O emissions from bird housing has been reported by several researchers (Wathes et al., 1997; Miles et al., 2006; Moore et al., 2011; Miles et al., 2014), a N_2O emission rate while litter windrowing during downtime is not available and has not yet been reported.

This study directly compares the NH_3 and N_2O emissions from two similar commercial broiler houses in a farm with and without windrowing management of built-up litter during downtime.

Materials and Methods

Experimental Site

This research was conducted in two tunnel-ventilated broiler houses on a commercial broiler farm in Arkansas in October 2012 and August 2013. One of the two houses was used as a control (without litter windrowing) and the other house (with litter windrowing) was used as a treatment house. In 2012, 2 d after the birds were harvested, the litter in the treatment house was windrowed (19 Oct. 2012), whereas, in 2013, the treatment house was windrowed 6 d after harvest (21 Aug. 2013). In the second year, the treatment in the two houses was switched. The dimensions of the houses were ~145 by 12.5 m. Each broiler house was equipped with 10 122-cm tunnel ventilation fans. Typical flock sizes for these houses were between 25,000 and 30,700 birds.

Gas emissions were measured between flocks to evaluate the effects of short-term in-house windrow composting. Gas concentrations were measured at two tunnel fans in each house that were operating continuously during the study period. The remaining eight tunnel fans in each house were not operated. A photoacoustic gas analyzer (PGA) (Innova model 1412, California Analytical) and multisampler (CBISS, California Analytical) were used to sequentially measure NH_3, N_2O, and CO_2 concentrations at each fan. Teflon tubing (6.35 mm, outer diameter) with a small particulate filter was installed inside each fan housing and connected to the PGA centrally located between the two houses. For the duration of the study, average ambient gas concentrations outside the houses were used as influent gas concentrations. The accuracy of gas concentration measured by PGA was evaluated immediately before and after each study period using calibrated gases. The relative errors were <0.8% for the three gases.

The ventilation rates were measured via cup anemometers (model 03101-5 wind sentry anemometer, R.M. Young) and data loggers (CR10X, Campbell Scientific). A single anemometer was mounted strategically in front of each of the four tunnel fans used. The anemometers measured every second, and the average wind velocity was recorded at 1-min intervals. The airflow rates of the exhaust fans were evaluated with the Fan Assessment Numeration System (FANS) (Gates et al., 2004). The airflow rates were correlated to the anemometer measurements. The anemometers were mounted in the fan transect such that the velocity measured would correspond to the ventilation rate measured by the FANS. Each of the four fans was evaluated with the FANS unit immediately before and after the study period. The signals from the two anemometers in the treatment house in 2012 were lost for a day. Because these fans operated continuously at constant ventilation rates, the average airflow rates of each fan were used to calculate the emission rate during that period. The emission rates of each gas were calculated by multiplying gas concentrations and ventilation rates. The gas concentrations were converted to mass concentration using the ideal gas law:

$$ER_i = Q(C_{f,i} - C_{o,i})PMW_i/(1000RT) \quad [1]$$

where ER_i = emission rate of gas i (g min^{-1}), Q = ventilation rate (m^3 min^{-1}), $C_{f,i}$ = gas i concentration in the fan housing (μL L^{-1}), $C_{o,i}$ = influent gas i concentration (μL L^{-1}), P = barometric pressure at the study site (atm), MW_i = molecular weight of gas i (g mol^{-1}), R = universal gas law constant (0.08206 L atm mol^{-1} K^{-1}), and T = air temperature (K).

Litter temperatures of both houses prior to windrowing were monitored at 10 points that represented the entire house litter (Fig. 1). The depth of litter for both houses before windrowing was about 10 cm. The height of roughly prism-shaped windrows varied from 22 to 61 cm; the width of the windrows varied from 1.80 to 3.18 m. Once windrowing started in the treatment house, temperatures at 10 points of the windrows were measured at three depths: 7.6 cm below the surface, at the middle, and at the bottom (1–2 cm above ground) of the litter. For the control house, only mid-depth litter temperatures were measured. In the second year, the litter temperatures of the treatment house were measured at the middle of the windrow.

Litter Sampling for C/N and Microbiological Analyses

Houses were divided into 10 sampling sites per house. In the treated house, five samples were taken from each windrow, and there were two windrows per house. In the control house, there were three zones: east, middle, and west. Three litter samples were collected from the east and west sides, and four samples were collected from the middle of the house. Windrows were sampled throughout the entire depth of the pile, mixed, and a 0.95-L freezer bag was filled with about 300 g of litter sample^{-1}. The control houses were sampled by removing about 0.2 m^2 of litter to the entire depth, mixing, and filling the freezer bag about 3/4 full (200–300 g of litter). These sampling sites were flagged and sampling sites were kept the same for both composting events. The litter samples were collected in 2013 from both houses, 1 d after birds were removed and at the end of the study (i.e., 5 d after windrow started).

Microbiological Analyses

All litter and compost samples were shipped overnight from Arkansas to Beltsville, MD, in insulated coolers with frozen gel packs and were stored immediately on receipt at 4°C for 24 to 48 h until analyses were initiated. Primary suspensions were prepared containing 20 g (in 2012), and 30 g (in 2013) of samples, as received, in a sterile Whirl-Pak filter bag (Nasco) with 180 (in 2012) or 270 mL (in 2013) sterile phosphate-buffered water (1:10 dilution). Sample preparation bags were manually mixed for 2 min to thoroughly saturate and suspend the dry litter materials with diluent. Controls consisted of spiked samples prepared as described above, except that samples were inoculated with 0.5 mL of 10^{-6} CFU mL^{-1} 18-hr Trypticase soy broth (TSB; Difco, Becton Dickinson Co.) cultures of reference strains of *E. coli* ATCC 25922 and *Salmonella enterica* serovar Typhimurium ATCC 14028. Serial 10-fold dilutions up to 10^{-5} in sterile phosphate-buffered water were prepared and spiral-plated (50 μL) in duplicate (WASP2, Microbiology International) onto MacConkey agar (MAC, Difco) and xylose lysine tergitol-4 agar (Difco) for detection of *E. coli* and *Salmonella* spp., respectively. Plates were incubated at 37°C for 18 h for *E. coli* and *Salmonella* and then examined for the presence of characteristic colonies. In the absence of detectable colonies on unspiked samples, a second set of primary suspensions was prepared as described above but were used for analysis by the most probable number (MPN) procedure. For detection and enumeration of *E. coli*, sample suspensions (1.0 mL) were then diluted 1:2 in double-strength Lauryl Tryptose broth (LTB; Oxoid, Thermo Scientific) in a 48-well, deep-well plate (VWR) and then serially diluted 1:10 in 1.8 mL LTB broth. Each dilution through the 10-fold series, including 10^{-5}, was replicated eight times. Plates containing MPN dilutions were incubated at 42°C for 18 h, and then each well of all dilutions was struck onto MAC to determine the presence of *E. coli*. The detection limit for MPN assay was −0.12 $\log_{10}$ MPN g^{-1} dry wt.

For detection and enumeration of *Salmonella* by MPN, after incubation at 4°C for 18 h, 3-μL drops from each LTB well were dispensed onto the surface of Modified Semisolid Rappaport-Vassiliadis (MSRV, Thermo Scientific) agar and incubated at 37°C for 18 h. Presumptive positive colonies from each MSRV plate were streaked for isolation onto XLT-4 agar medium plates and incubated at 37°C for 24 h. Presumptive positive isolates from XLT-4 were confirmed as *Salmonella* using biochemical (triple sugar iron and lysine iron agars, and urea broth) and serological (poly-O antiserum, Becton Dickinson Co.) methods. Percentage moisture content of samples was determined by drying duplicate 10-g samples at 105°C for 24 h, with calculations according to Hayes et al. (2000). Results were calculated as MPN *E. coli* or *Salmonella* per gram (dry weight) on the basis of positively confirmed isolates that corresponded to the MPN.

Statistics

Statistical results included means, standard deviations, ANOVA, comparison of linear regression lines of cumulative gas emission from the two houses, and LSD at a 0.05 probability level ($LSD_{0.05}$) for multiple paired comparisons among means using statistical software GraphPad Prism (Motulsky, 2017).

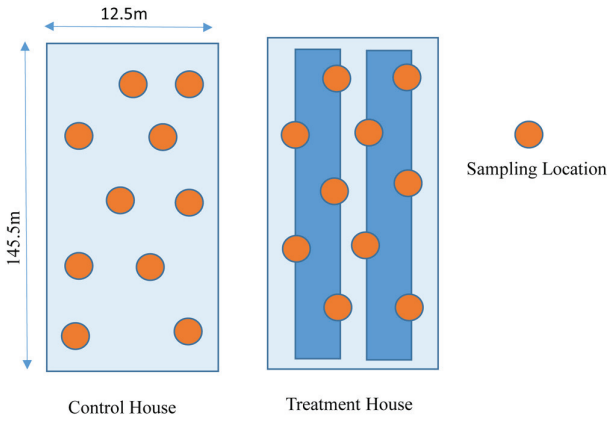

Fig. 1. Sampling locations of control and treatment houses.

Results and Discussion

Litter Temperature

The litter temperature of the control house in 2013 (27.9 ± 2.6°C) was 3°C higher than in 2012 (24.0 ± 2.5°C) due to a higher ambient temperature in August 2013 (28.4 ± 2.0°C) than in October 2012 (19.6 ± 6.1°C). The mid-depth windrowed litter temperature in the treatment house peaked at 53.2°C on Day 2 and then declined to 47.2°C by Day 5 in 2012 (Fig. 2). The average mid-depth temperature of the windrowed litter in the treatment house in 2012 was 43.4 ± 13.3°C. The mid-depth windrowed litter temperature reached 45.1°C with an average temperature of 42.9 ± 4.3°C in 2013. Within the windrowed litter, there was a vertical temperature gradient; the highest temperature (43.4 ± 13.3°C) was achieved at the mid-depth. The near-surface and the bottom temperatures were 32.2 ± 10.3°C and 34.0 ± 9.3°C, respectively. These temperatures were significantly lower than those

in the middle of the windrowed litter (P = 0.009 between near-surface and mid-depth, P = 0.075 between bottom and mid-depth) due to evaporative, convective, and conductive heat losses from the surface to the ambient air and floor (Kaiser, 1996; Ro et al., 1998).

Microbiological Analyses

Only three samples of control litter per year per poultry house had a single confirmed *E. coli* or *Salmonella* colony from the direct-plated sample suspensions. Mean population densities by MPN also were exceedingly low (0.8–1.2 log MPN g^{-1}) for the samples for which positive *E. coli* or *Salmonella* were detected and confirmed. None of the windrowed litter samples from either year yielded confirmed colonies of *E. coli* or *Salmonella* from spiral-plated or MPN-processed samples. Both *E. coli* and *Salmonella* were recovered from control and windrowed litter samples that were spiked with the reference strains, indicating that the detection methods were sensitive enough to detect the presence of viable *E. coli* or *Salmonella* at the MPN detection limit. In addition to *E. coli* and *Salmonella*, all samples were assayed for viable *Staphylococcus* and *Enterococcus* using media and dilution plating, as described by Lu et al. (2003). No viable *Stapylococcus* or *Enterococcus* were detected in the control or windrowed litter samples analyzed. Percentage moisture content for the control litter samples ranged from 35 to 38%, and for windrowed litter samples it ranged from 30 to 34%.

Several factors contributed to these results, including the relatively low moisture content, the uneven moisture and microbial distributions at different sample sites within the house, and the high NH_3 concentrations in the litter and the house. All of these factors have been reported to negatively affect *Salmonella* survival (Himathongkham et al., 1999; Hayes et al., 2000; Buhr et al., 2007; Ottoson et al., 2008). In the current study, the status of the flock with regard to vaccination against *Salmonella* or any other pathogen was not revealed to the research team. With low baseline and postwindrowing populations, we could not conclude that windrowing liter substantially reduced the targeted bacterial populations. Thermophilic composting accentuates the exposure of the litter microflora to combined stressors of elevated heat, ammonia, and decreasing water availability, which together contribute to pathogen destruction. Although we only tested the windrowed litter without turning, the recommended practice, also applicable to emergency control of avian disease outbreaks, involves turning the windrow multiple times to facilitate the exposure of surface materials to high temperatures in the core of the composting mass (Erickson et al., 2010; USDA-APHIS, 2016).

Ammonia Emission

The NH_3 concentrations and the emission rates of the two houses before windrowing were very similar, indicating the conditions of the two houses could be assumed as virtually identical (Fig. 3). Because the ventilation was continuous and its rates were constant, the NH_3 emission rate closely follows the NH_3 concentration pattern, as explained by Eq. [1]. The 2012 average NH_3 concentrations before windrowing were 10.6 ± 2.9 and 10.0 ± 2.8 μL L^{-1} for the control and treatment houses, respectively. In 2013, the NH_3 concentrations before windrowing were 12.5 ± 2.3 and 12.1 ± 3.1 μL L^{-1} for the control and treatment houses, respectively. After windrowing started, the NH_3 concentration and the emission rate of the treatment house became higher than that of the control house (Fig. 4, Table 1). The NH_3 concentrations of the control house during the 5-d windrowing period ranged from 7.8 to 22.6 and 8.9 to 21.5 μL L^{-1} in 2012 and 2013, respectively. The NH_3 concentration of the treatment house ranged from 10.3 to 52.0 μL L^{-1} in 2012 and 9.2 to 40.6 μL L^{-1} in 2013. Also, the NH_3 concentrations of both houses appeared to follow the diurnal ambient temperature changes (Fig. 5).

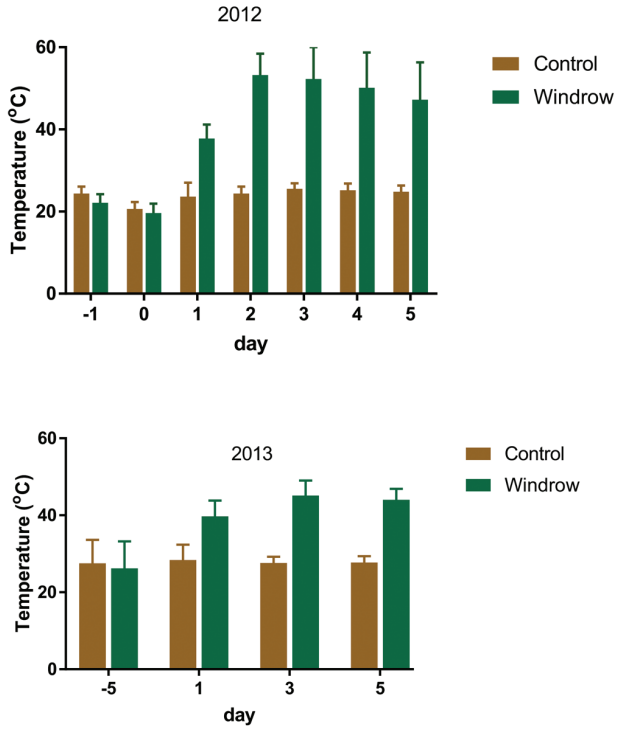

Fig. 2. Average litter temperatures of control and windrowed houses in 2012 and 2013.

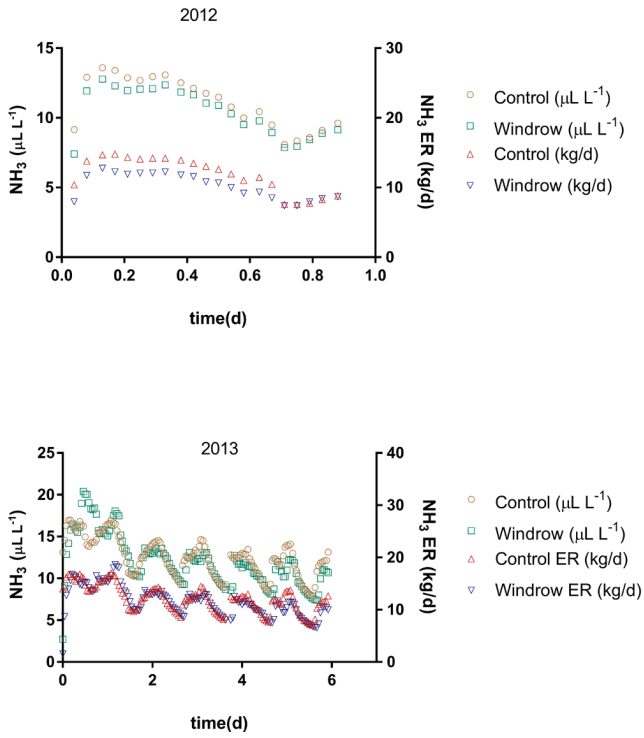

Fig. 3. Similar NH_3 concentrations and emission rates (ER) of both houses before windrowing.

The overall average NH_3 emission rates of the control house were 14.6 ± 3.5 kg d^{-1} $house^{-1}$ in 2012 and 12.8 ± 2.5 kg d^{-1} $house^{-1}$ in 2013 (Table 1). These NH_3 emission rates from the control house were similar to the downtime NH_3 emission rates of 13.4, 15.2, and 15.3 kg d^{-1} $house^{-1}$ from empty broiler houses with built-up litter (Topper et al., 2008; Moore et al., 2011) but were higher than 6.32 to 11.91 kg d^{-1} $house^{-1}$, reported by Burns et al. (2007). The NH_3 emission rates from the treatment house were higher than those from the control house for both years. The NH_3 emission rates from the treatment house were 26.2 ± 8.9 kg d^{-1} $house^{-1}$ in 2012 and 16.6 ± 5.2 kg d^{-1} $house^{-1}$ in 2013. A similar NH_3 emission rate (19.4 kg d^{-1} $house^{-1}$) from a windrowing house was reported by Liang et al. (2010), but the authors subsequently reported a lower emission rate, 8.77 ± 8.27 kg d^{-1} $house^{-1}$ (Liang et al., 2014).

The lower NH_3 emission rate in 2013 might be due to a lower NH_3 in the litter after waiting 6 d before windrowing in 2013, compared with only 2 d in 2012. More NH_3 in the litter was volatilized from the treatment house in 2013 during the 6-d waiting period than in 2012 with only a 2-d waiting period. The total NH_3 emitted before windrowing from the treatment house in 2013 (68.4 kg) was much higher than that from the treatment house in 2012 (8.9 kg).

N_2O Emission

The N_2O emissions from the two houses before windrowing were similar, as occurred with NH_3, indicating similar conditions of the two houses before treatment. Once windrowing started, the average N_2O concentrations of the treatment house (0.61 ± 0.16 μL L^{-1} in 2012 and 1.12 ± 0.5 μL L^{-1} in 2013) were significantly higher than those of the control house (0.33 ± 0.02 μL L^{-1} in 2012 and 0.48 ± 0.16 μL L^{-1} in 2013), as shown in Table 1 and Fig. 6. The corresponding N_2O emission rates from the treatment house were 0.92 and 2.38 kg d^{-1} $house^{-1}$ in 2012 and 2013, respectively. It is suspected that the decreased amount of NH_3 emitted with the increased N_2O emission in 2013 from both houses was because more N_2O formed from denitrification of nitrate in the litter during the longer waiting period (Ro et al., 2006). As an alternative explanation, N_2O could also be produced by aerobic nitrifiers in the litter (Bremner and Blackmer, 1978). The N_2O concentration of the empty treatment house was comparable with that of the broiler house populated with live birds measured by Miles et al., 2014 (0.47–1.41 μL L^{-1}). Although the N_2O emission rates of the control house (0.10 and 0.52 kg d^{-1}) were lower than the average emission rate (2.3 ± 1.7 kg d^{-1}) of the broiler house with live birds (Miles et al., 2014), the emission rates of the treatment house (0.92 and 2.38 kg d^{-1}) were comparable.

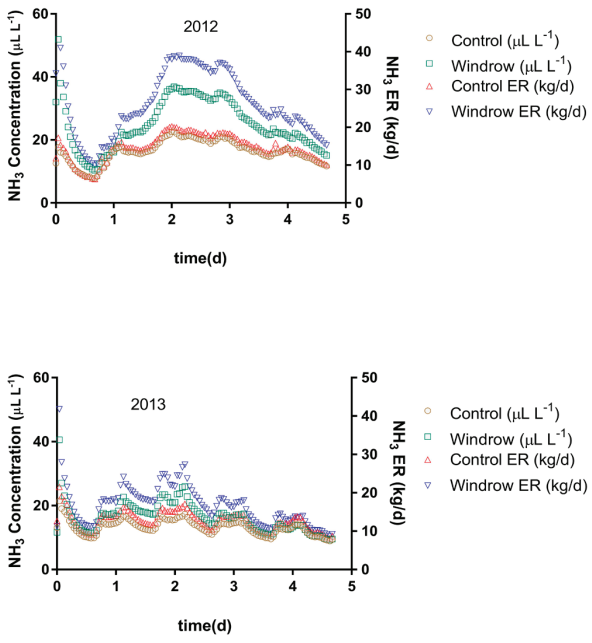

Fig. 4. Ammonia concentrations and emission rates (ER) of both houses after windrowing.

Total NH_3 and N_2O Emissions from Broiler Housing

The total NH_3 and N_2O emissions from broiler housing can be estimated by adding the emission while growing birds and the emission between flocks. Miles et al. (2014) developed quadratic polynomial equations for both NH_3 and N_2O emission rates from a commercial broiler house (27,000–28,300 birds) as a function of day of flock. Using the quadratic equations, the total emission per bird can be estimated as:

$$E_i = \left[\int_0^{T_{bird}} \left(at^2 + bt + c\right)dt + \mathrm{ER}_{i,cont}T_{cont} + \mathrm{ER}_{i,wind}T_{wind}\right] 1000/\beta \quad [2]$$

where E_i = total emission of gas i (g $bird^{-1}$); a, b, and c = 0.0094, 0.2542, and 3.5663 for NH_3 and 0.0022, 0.0153, and 0.5968 for N_2O, respectively; $ER_{i,cont}$ = average emission rate of gas i from

Table 1. Average exhaust gas concentrations, emission rates, and the total masses emitted.

Year	Treatment	Concentration	Emission rate	Total emitted†
		μL L^{-1}	kg d^{-1}	kg
		NH_3		
2012	Control	16.3 ± 3.7‡	14.6 ± 3.5a§	68.3
	Windrow	25.0 ± 8.0	26.2 ± 8.9b	122.0
2013	Control	13.2 ± 2.4	12.8 ± 2.5a	59.5
	Windrow	16.3 ± 4.8	16.6 ± 5.2c	77.8
$LSD_{0.05}$		2.4		
		N_2O		
2012	Control	0.33 ± 0.02	0.10 ± 0.03a	0.46
	Windrow	0.61 ± 0.16	0.92 ± 0.46b	4.31
2013	Control	0.48 ± 0.16	0.52 ± 0.44c	2.39
	Windrow	1.12 ± 0.50	2.38 ± 1.41d	11.18
$LSD_{0.05}$		0.3		
		CO_2		
2012	Control	500 ± 14	250 ± 40a	1150
	Windrow	632 ± 71	660 ± 200b	3080
2013	Control	530 ± 51	360 ± 140c	1670
	Windrow	619 ± 85	630 ± 240b	2940
$LSD_{0.05}$		74		

Treatment	Ventilation rate
	m^3 min^{-1}
Control	960 ± 23
Windrow	1091 ± 13
Control	1057 ± 3
Windrow	1098 ± 13

† Total gas emitted 4.7 d after onset of windrowing.

‡ Values ± SD.

§ Within columns, means followed by the same letter are not significantly different according to $LSD_{0.05}$ at $\alpha = 0.05$.

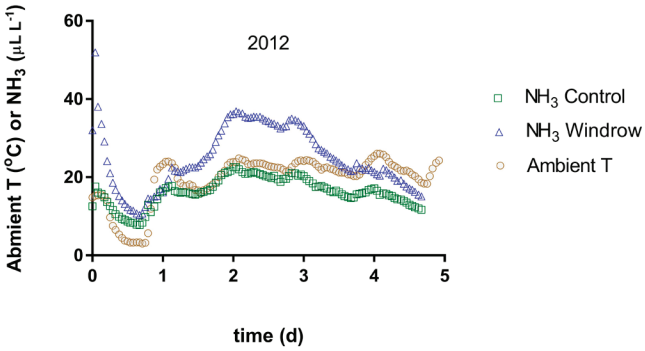

Fig. 5. Ammonia concentrations closely follow diurnal changes in ambient temperature (T).

control house (kg d^{-1} house^{-1}); $ER_{i,wind}$ = average emission rate of gas *i* from windrowing house (kg d^{-1} house^{-1}); *t* = day of flock; T_{bird} = day of flock (d); T_{cont} = days without windrowing litter (d); T_{wind} = days with windrowing litter (d); and β = number of birds in the house.

Using the average NH_3 emission rate determined from this study (13.7 and 21.4 kg d^{-1} house^{-1} for control and treatment houses, respectively), the total NH_3 emission per bird from a broiler house growing 25,000 birds for 42 d with 4 d of litter layout and 10 d of windrowing litter between flocks was calculated to be 35.0 g bird^{-1}. It consisted of 24.2 g bird^{-1} from flock growth and 10.8 g bird^{-1} from downtime litter management. The NH_3 emission rate from flock growth (24.2 g bird^{-1}) was similar to 25.8 g bird^{-1}, reported by Eugene et al. (2015). About 31% of NH_3 emission per bird was attributed to the downtime litter management. Similarly, the total N_2O emission per bird was 4.43 g bird^{-1} consisting of 3.72 g bird^{-1} from flock growth and 0.71 g bird^{-1} from downtime litter management. Unlike NH_3, only 16% of N_2O emission was attributed to the litter management.

CO_2 Emission and C/N Ratio

The respiration rates as indicated by the CO_2 emission rate of the treatment house were not significantly different for the 2 yr (Table 1). The control house respiration rate in 2013 was only slightly higher than that in 2012. However, the treatment house CO_2 emission rates were significantly higher than those of the control house due to higher windrowed litter temperature. Since both C and N were emitted from the bird houses, the litter C/N ratio changed over the study period. The emission of NH_3 and N_2O from the litter resulted in an increase in C/N ratios. The C/N ratios of the litter samples from the control house in 2013 significantly increased, from 9.0 ± 1.6 (1 d after removal of birds) to 10.3 ± 1.4 at the end of study period (P = 0.034, unpaired *t* test with Welch's correction). The C/N ratios of the litter samples from windrowing house at the same period also increased slightly from 10.4 ± 3.4 to 11.2 ± 1.8; however, the difference was not statistically significant (P = 0.263, unpaired *t* test with Welch's correction). The differences of the C/N ratios of the two houses on both sampling events were not statistically significant at P = 0.05 (unpaired *t* test with Welch's correction).

Conclusions

The windrowed litter temperature in the treatment house was significantly higher than that of the control house. The impact of

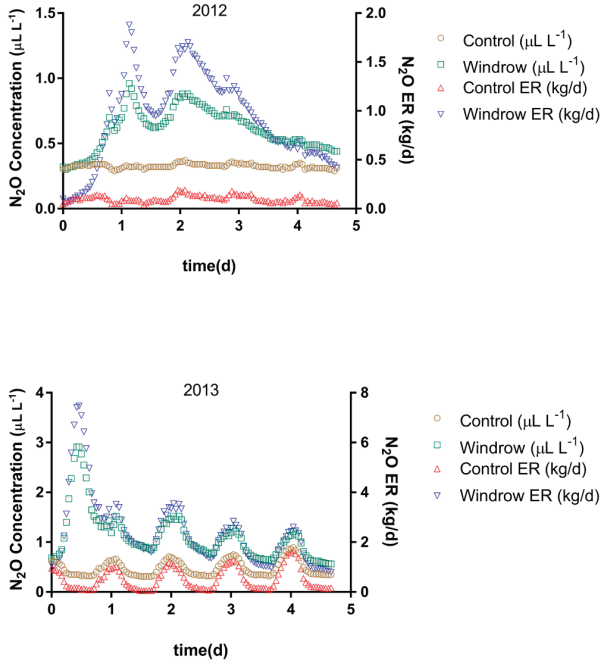

Fig. 6. N_2O concentrations and emission rates (ER) of the control and treatment houses.

downtime windrowing litter management on pathogen reduction is inconclusive because of lower microbial recoveries measured. Both *E. coli* and *Salmonella* spp. were recovered sporadically and at low concentrations (0.8 to 1.0 MPN g^{-1}) from the control litter. However, these microorganisms were not recovered at all from the windrowed litter in either year. The NH_3 emission rates from a commercial broiler house during downtime windrow litter management were 26.2 kg d^{-1} house^{-1} in 2012 and 16.6 kg d^{-1} house^{-1} in 2013, significantly higher than those from the control house. The N_2O emission from the windrowing house (0.92 and 2.38 kg d^{-1} house^{-1} in 2012 and 2013, respectively) was also significantly higher than those of the control house (0.10 and 0.52 kg d^{-1} house^{-1} in 2012 and 2013, respectively). These higher gas emission rates were attributed to the higher windrowed litter temperature. For a typical broiler operation growing 25,000 birds for 42 d with 14 d of downtime litter management involving 10 d of windrowing, the total NH_3 and N_2O emissions were 35.0 and 4.43 g bird^{-1}, respectively. The gas emission from the downtime litter management was attributed to 31 and 16% of the total NH_3 and N_2O emissions, respectively. Although in-house windrowing of litter is recommended by the USDA's Animal and Plant Health Inspection Service as a protocol to control disease outbreaks such as avian influenza, producers should consider the increased NH_3 and N_2O into the environment and the additional labor cost for the recurrent use of in-house windrowing as a regular broiler litter management practice.

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