The Potential for Plants to Trap Emissions from Farms with Laying Hens: 2. Ammonia and Dust

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Primary Audience: Farm Owners, Poultry Managers, Agricultural and Residential Environmentalists

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SUMMARY

The potential for plants to trap NH_3 and dust [particulate matter (PM)] discharged from a layer house through the exhaust fans was evaluated at The Pennsylvania State University Poultry Education and Research Center in August 2006. Poultry and livestock NH_3 emissions are a concern for air quality, surface deposition, and animal and human health. Particulate matter is a human health concern as well and is regulated by the United States Environmental Protection Agency in nonattainment areas. A vegetative buffer comprising 5 tree species was planted in pot-in-pot containers in 5 rows downwind from 4 henhouse fans, with 1 control row of plants upwind from the fans. When measured with a photoacoustic NH_3 detector at fan elevation (1.5 m), NH_3 concentrations decreased sharply ($P \leq 0.0001$) with greater distance, from 71.1 ppm at 0 m (at the fan) to 2.1 ppm at 5.5 m (between rows 2 and 3), 0.3 ppm at 10 m (after row 5), and 0.1 ppm at 50 m (control). This trend was also observed with colorimetric dosi-tubes and a photoacoustic detector at 0.3- and 3.0-m elevations. Significantly lower NH_3 concentrations were recorded at both the 0.3- and 3.0-m elevations in the presence of the trees compared with when the trees were removed from their pot-in-pot containers, suggesting that a portion of the atmospheric NH_3 was being trapped by the plants. This was further supported by greater foliar N concentrations in plants when measured downwind from the fans ($P \leq 0.0001$). Dust concentrations sampled downwind from the fans were greatest at 2.5 m and decreased linearly to 50 m ($P \leq 0.0001$). Plant $PM_{2.5}$, PM_{10}, and total PM washed from the foliage showed the same significant linear trend with greater distance from the fans. Plants also showed unique species differences in their capacity to trap and hold NH_3 and PM that can be applied in practical recommendations. These findings indicated vegetative buffers are capable of trapping NH_3 and PM fan emissions from poultry facilities.

Key words: plant, ammonia, dust, foliage nitrogen, laying hen

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DESCRIPTION OF PROBLEM

The environmental impacts of atmospheric NH_3, including soil acidification, land N deposition, and eutrophication of fresh and salt water ecosystems [1–4], are significantly affected by animal agriculture and manure fertilization [4, 5]. In the national emission inventory report of the United States Environmental Protection Agency [5], the poultry sector was credited with approximately 24% of total NH_3 emissions from animal agriculture in 2002 and is projected to be the main contributor by 2030, implying that efforts to deal with this issue are warranted.

The major approaches to mitigate poultry farm NH_3 emissions are to reduce NH_3 generation and trap emissions. Dietary and management strategies can significantly reduce the generation and volatilization of NH_3 and reduce dust and odor emissions from the farm [6–12]. Another approach to trap emissions once they are generated is the application of vegetative shelterbelts as filters for poultry farm emissions. The goal is to decrease the dispersion of fan emissions that include NH_3 discharged from poultry and livestock farms before these emissions escape into the atmosphere [13, 14]. This is based on the capability of the plant foliage to utilize aerial NH_3-N through its stomata by means of the glutamine synthetase-glutamate synthase pathways [15]. Van der Eerden et al. [2] reported that at the appropriate concentrations, NH_y ($NH_3 + NH_4^+$) would favor plant growth. Malone et al. [14] observed reduced NH_3 concentrations (46%) on a roaster farm downwind from a vegetative buffer (16.8 m distance) comprising bald cypress, Leyland cypress, and red cedar (7.6 m wide) when compared with concentrations measured near tunnel fans (9.2 m). In a field study in 2004, we measured greater foliar N concentration among the plants sampled at 11 to 18 m downwind from the fans compared with those sampled 48 m away from the fans on commercial poultry farms [16]. Subsequent refined experiments in 2005 [17] confirmed this finding and showed a significant decrease in aerial NH_3 concentration from a layer house for distances up to 50 m from the fans concurrent with reduced foliar N levels, particularly at a distance of 3.5 to 10 m downwind from the fans.

Emissions discharged through the exhaust fans from a livestock building may consist of gases and complex aerosols, including moisture with bacteria, fungi, endotoxins, grain dust, and animal proteins [18]. Because of its reactive properties with other gases and water, NH_3 readily forms aerosols (vapor phase) and is adsorbed onto dust particles (particulate phase) [18, 19], thus moving in the gaseous and solid phases of air emissions. Like NH_3, dust, which can carry various bioaerosols and pathogenic microorganisms, has the potential to cause health problems for poultry, livestock, and their caretakers [18]. Therefore, efforts to reduce NH_3 will help reduce other farm emissions, including dust. Because plant foliage has the capability of trapping NH_3-N, it is likely it has the physical capacity of trapping dust. Studies using physical barriers and walls (biofilters or scrubbers) as windbreaks to reduce farm emissions have been reported [12, 20, 21], but very few studies have looked at the potential of vegetation to trap fan emissions, particularly dust from poultry and livestock housing. Among those efforts, Malone et al. [14] observed not only an NH_3 reduction downwind from 3 rows of trees, but also a significant decline in dust levels (approximately 49 ± 27%) from 9.2 to 16.8 m away from the fans. In a review article, Leuty [22] estimated that 35 to 55% of livestock dust could be removed by vegetative shelterbelts, depending on wind characteristics and shelterbelt density. Therefore, in addition to reevaluating the results of our previous study [17] on the potential of vegetation to trap NH_3 around poultry farms, the current study was conducted to investigate the potential of plant foliage to trap dust particulates.

MATERIALS AND METHODS

Henhouse

Ammonia measurements and foliage samples for N and DM determination were taken at a layer house (Figure 1) at The Pennsylvania State University Poultry Education and Research Center (University Park, PA) in August 2006. The house kept 661 Single Comb White Leghorn laying hens, 20 wk old (maximum capacity of this room was 3,000 hens) and given a standard layer diet at the time of the study. In addition to the main ceiling air inlets, this part of the building had a ventilation system comprising 7 side-wall inlets (4 on the left and 3 on the right) along with four 61-cm exhaust fans (in the front) and a controller based on temperature and static pressure at 14 Pa. Each of the fans had a connecting hood (Figure 2; 76 × 86 cm opening at a 15° angle) directing exhaust air to the ground outside the house. These were not unlike the covered fan banks on commercial layer houses that light trap and direct exhaust air to the ground. All fans were set to run at the same speed (2,500 rpm), and the air speed of the fans averaged 333 m/min [23] throughout the study, with a calculated discharge of approximately 97 m^3/min per fan.

Source of Additional NH_3

Because henhouse density was not at capacity at the time of the study, additional anhydrous NH_3 was released from a 150-L anhydrous NH_3 tank into the intake of the 4 fans to increase the NH_3 discharged. The tank, which was pressure-

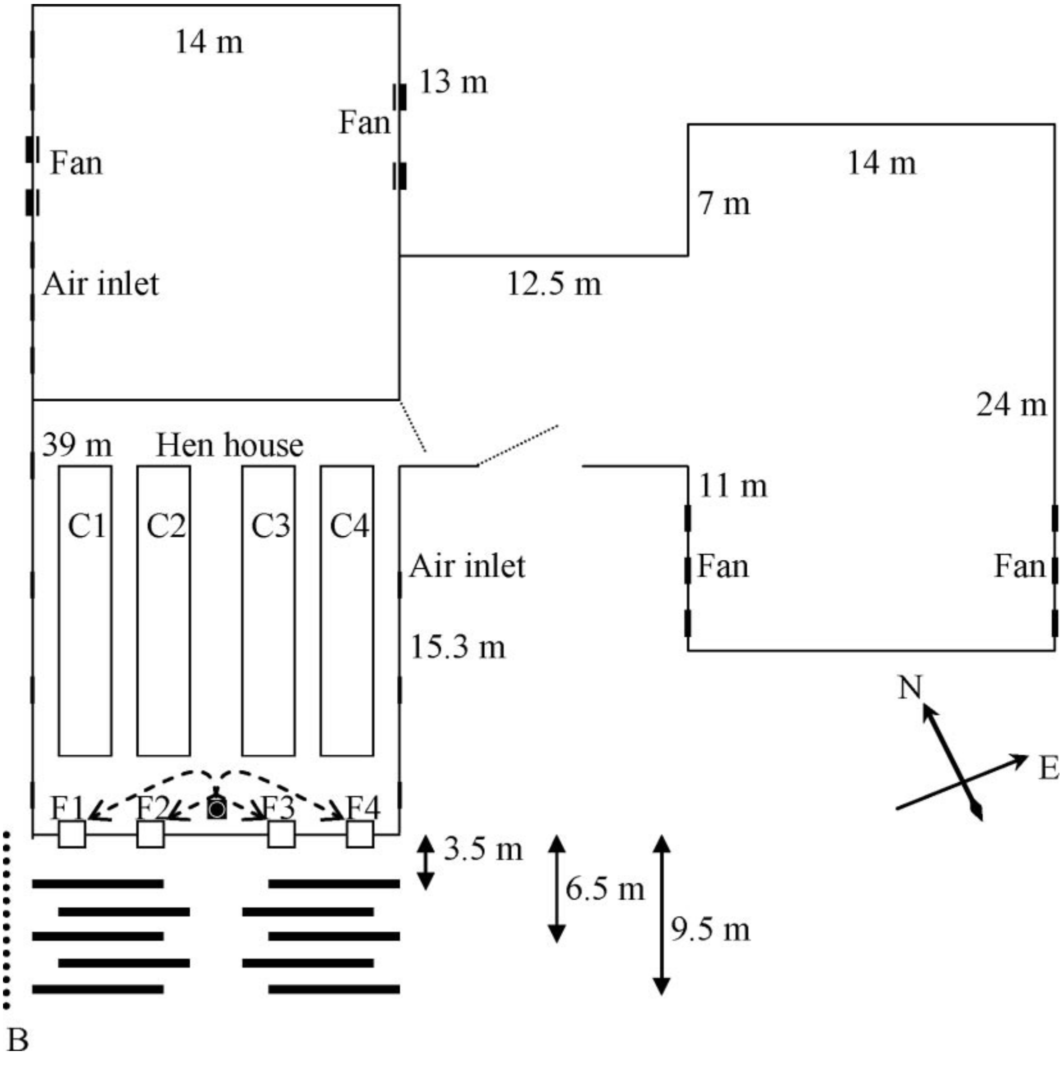

Figure 1. Trees planted in the pot-in-pot system arranged in rows downwind from four 61-cm exhaust fans from the henhouse. C = cage rows; F = fans; circle inside black square = NH_3 tank; bold lines in front of the fans indicate the position of tree rows; B = vertical dotted line southwest downwind of the fans indicates the barrier curtain. Control trees (50 m upwind away from the fans) and a portable weather station established 28 m southwest of the henhouse are not shown in this figure.

regulated at 1.79 kg/cm^2, was connected with a T-connector to 2 equal lengths of polyvinyl chloride tubing. Each end of the tubing was further connected with a T-connector to 2 glass flow meters [24] and set to release NH_3 at 1.5 L/min via a manifold 0.64-cm polyvinyl chloride tubing (with 5 holes) for 8 h (from 0830 to 1630 h) on each NH_3 measuring day. Each of the manifolds was mounted diagonally across each fan intake at a 30-cm distance from the blades. A 2.5-m-high, 10-m-long shade cloth curtain was built southwest of the henhouse along the left side of the tree rows (Figure 1) to reduce the impact of prevailing winds on NH_3 measurements.

Pot-in-Pot Trees

Five rows of 10 holes (0.5 m diameter; 0.4 m deep) were drilled in the ground downwind from the exhaust fans of a layer house and fitted with 76-L female pots. Five tree species [Canaan fir (*Abies balsamea* var. *phanerolepis*), hackberry (*Celtis occidentalis*), juniper (*Juniperus communis* L.), lilac (*Syringa* × *prestoniae*), and streamco willow (*Salix purpurea* L.)] were chosen to represent evergreen (fir and juniper) and deciduous trees (hackberry, lilac, and willow) in this study. Willow was selected based on our previous experiences in the field, where it appeared as one of the fastest growing deciduous species and survived placement at close proximity to commercial poultry house fan emissions [16]. The livability and buffer functionality of juniper and fir as aerial NH_3 traps were also recognized in our previous pot-in-pot study [17]. All the trees in the present study were originally purchased between 2001 and 2003 from a commercial nursery and grown at The Pennsylvania State University Landscape Management and Research Center and were transferred into 76-L male pots containing NX-6 pine bark media [25] in late summer of 2004 (all plants were between 5 and 8 yr old). All the male pots containing media and trees were fitted into the 76-L female pots and grid (Figure 2). This pot-in-pot system allowed us to remove all the trees from the exhaust field to measure NH_3 emissions under the experimental conditions with no trees present. The first row of trees was 3.5 m downwind from the fans, and the distance between 2 rows was 1.5 m. Within a row, the distance between trees was 1.2 m. An additional row of 10 control trees was approximately 50 m away upwind from the fans. There were 2 plants per species in each row downwind and upwind from the fans. All the plants were irrigated automatically with individual emitters twice daily for 10 min/d, with the time adjusted as required. In June 2005, each plant was fertilized with a one-time dose (28 g) of Osmocote-Plus 15 nitrogen-9 phosphorus-12 potassium (15N-9P-12K) controlled-release fertilizer [26]. At the beginning of the NH_3 measurements and foliage sampling (August 2006), plant heights were measured and averages were determined (in cm) as 243 ± 28 (fir), 355 ± 61 (hackberry), 160 ± 12 (juniper), 175 ± 18 (lilac), and 196 ± 15 cm (willow), respectively.

Parameter Measurements

Ammonia measurements were made between 1000 to 1500 h daily under each condition (trees vs. no trees) and replicated 3 times. On d 1 and 2, NH_3 was measured with all the trees in their pots downwind from the 4 exhaust fans. On d 3, those trees located downwind from the 2 fans on the right side of the henhouse were removed, whereas those trees in front of the 2 left-side fans remained on site and NH_3 measurements were performed. On d 4, the remaining trees were removed from the left side, replicating the no-tree condition, and NH_3 measurements were taken and repeated on d 5. On d 6, trees downwind from the 2 right-side fans were replaced and NH_3 measurements were taken to complete the third replicate of NH_3 measurement under each condition.

Under each condition, NH_3 was measured in front of each fan at 0 m (on the safety grill of the fan hood), 5.5 m (between rows 2 and 3 of the trees), 10 m (after row 5), and 50 m (control row). Each measurement was taken at 3 different heights (0.3, 1.5, and 3.0 m) except at the surface of the hood. The 1.5-m height matched the height of the fan. A photoacoustic NH_3 detector, capable of detecting NH_3 at the parts per billion level [27], was used to measure ambient NH_3 concentration (≥7 readings) over a 5-min duration at each location per day. Passive colorimetric dosi-tubes [28] were also hung at 1.5 m on a metal post in each location for 6 to 8 h/d (0800 to 1600 h) to back up the photoacous-

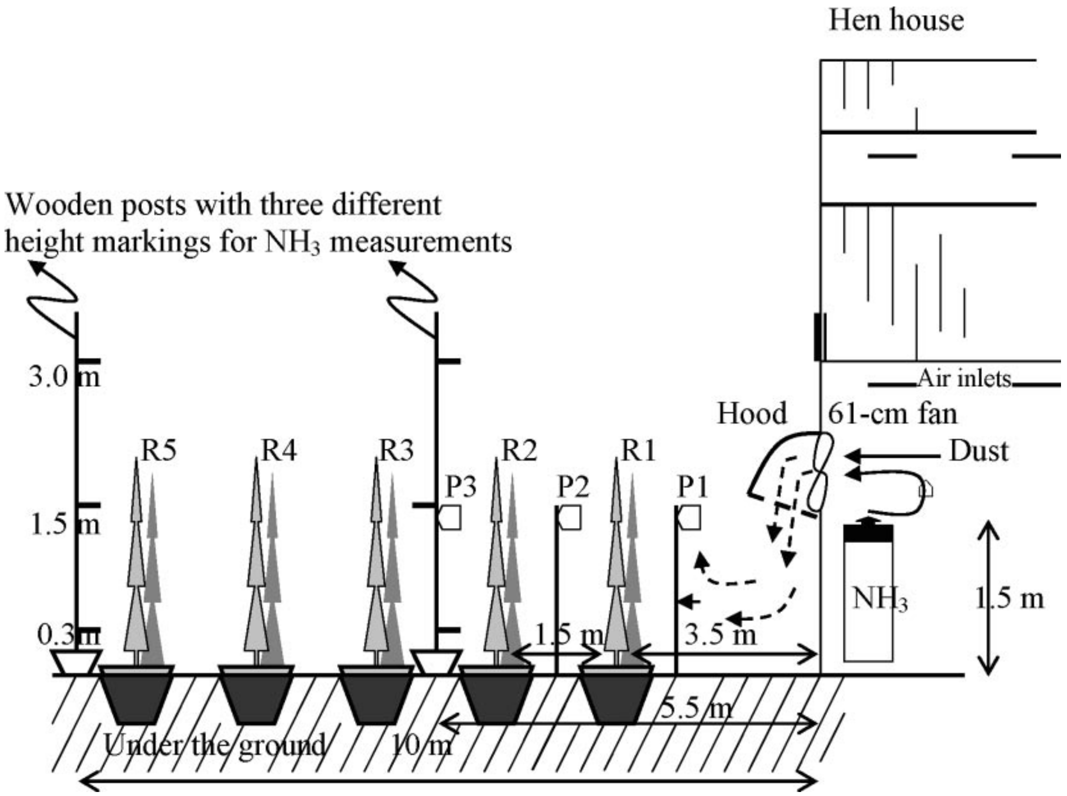

Figure 2. Side view of the henhouse showing a 61-cm exhaust fan with hood and pot-in-pot containers with trees. R1 to R5 = male potted trees fitted into female pots in the ground arranged in rows R1, R2, R3, R4, and R5. Trees actually varied in height; the average heights of the trees at the beginning of NH_3 measurements were 243 ± 28 cm (fir), 355 ± 61 cm (hackberry), 160 ± 12 cm (juniper), 175 ± 18 cm (lilac), and 196 ± 15 cm (willow). P1 to P3 = locations where air pumps with cassettes to capture dust were established; the barrier curtain located on the southwest side downwind from the fans is not shown.

tic readings during the 3-d monitoring under each condition. The color change of the indicator within the scaled dosi-tubes from blue to yellow was read and divided by the number of hours to determine the average NH_3 concentration in parts per million per hour. The aerial climatic conditions were monitored continuously throughout the study. Temperature and RH were recorded by using a data logger [29] hung at 1.5 m among the trees and 6.5 m downwind from the fans. Wind speed and direction were monitored with a portable weather station [30] established at 28 m southwest of the layer house. All data were collected on calm days. Smoke was used before the study to evaluate airflow and revealed exhaust air passing through the trees and not simply blown over the top.

Foliar tissue was sampled from each tree species under each condition. This was done at the end of the NH_3 recording period at approximately 1630 h. Samples were sent to The Pennsylvania State University Agricultural Analytical Services Laboratory for total N and dry weight analysis. The DM of foliage was calculated from the difference of fresh and dry weight over the fresh weight and presented as a percentage value.

Dust emission measurements were made by using personal air sampling pumps [31] after each NH_3 monitoring day. Dust and NH_3 could not be evaluated simultaneously because of potential damage to the photoacoustic filters from dust deposition. Approximately 1 kg of poultry dust/h was released into each fan intake (in the henhouse) for 5 to 8 h/d to increase the dust discharged. Replicate sampling pumps were placed downwind from each fan at 3 distances: 2.5 m (between the fans and the first row of trees), 4.5

m (after the first row of trees), and 6.0 m (after the second row of trees). Two additional pumps were placed at 50 m from the fans under each condition as controls.

Plant foliage from juniper and willow, to represent evergreen and deciduous tree species, respectively, were sampled after dust measurements. Fresh foliage samples were packed in bottles on ice and shipped overnight to the Department of Natural Resource Ecology and Management Laboratory at Iowa State University for particulate matter (PM) weight per foliage area analysis (mg/cm^2) [32]. The PM determinations were for particles with aerodynamic equivalent diameters of less than 2.5 µm ($PM_{2.5}$) and 10 µm (PM_{10}), greater than 10 µm ($PM_{>10}$), and total PM.

Experimental Design and Statistical Analysis

A completely randomized block design was applied in this study, with either 2 or 4 fans considered as blocks. Three mathematical models were used to analyze aerial NH_3 concentration and dust, plant foliar N and DM concentrations, and plant foliage particulates. For plant foliar N and DM analyses, only 2 fans were considered as blocks instead of 4 fans, as in the NH_3 data analysis. The 2 left-side fans (fans 1 and 2) represented block 1 and the other 2 right-side fans (fans 3 and 4) represented block 2. This was because all 5 plant species (2 plants each) were planted randomly downwind from each 2 pair of fans. All the data were subjected to 2-way ANOVA by using the GLM procedures of SAS, followed by the Bonferroni test [33] to distinguish the significance ($P \leq 0.05$) among treatment means.

RESULTS

Variation existed for all climatic parameters on a daily basis (Table 1). Wind direction was quite variable regardless of the day or condition, with slow wind speeds averaging from 5.1 ± 0.2 km/h when the trees were in place to 6.9 ± 1.5 km/h when no trees were on site. The predominant wind direction was west-southwest.

Day had a small but significant effect on NH_3 concentration, as measured with the photoacoustic detector at heights of 1.5 ($P \leq 0.05$) and 3 m

Table 1. Microclimatic conditions (temperature, RH, wind speed, and wind direction) during the measurement of NH_3 concentration downwind at the exhaust fans at the henhouse under 2 conditions (trees vs. no trees)[1]

Day[2]	Temperature			RH			Wind speed (and wind direction)		
	Trees	No trees	Average	Trees	No trees	Average	Trees	No trees	Average
	(°C)			(%)			(km/h)		
1st	23.4 ± 2.2	27.8 ± 1.3	25.6 ± 1.8	48.0 ± 5.7	34.4 ± 3.9	41.2 ± 4.8	5.2 ± 1.6 (N, WSW)[3]	7.6 ± 1.2 (WNW)	6.4 ± 1.4
2nd	27.1 ± 0.7	28.8 ± 2.3	28.0 ± 1.5	27.0 ± 3.3	54.1 ± 10.1	40.6 ± 6.7	4.8 ± 2.3 (WSW, W)	7.9 ± 1.9 (WSW)	6.4 ± 2.2
3rd	25.9 ± 1.7	25.9 ± 1.7	25.9 ± 1.7	39.5 ± 6.3	39.5 ± 6.3	39.5 ± 6.3	5.2 ± 2.6 (WSW, N)	5.2 ± 2.6 (WSW, N)	5.2 ± 2.6

[1] Data are presented as the mean ± SD.

[2] Measurement days (the first, the second, and the third days of NH_3 measurements were performed on d 1, 2, and 3 when the trees were in place, whereas the corresponding NH_3 measurements when the trees were removed from the pots were performed on d 4, 5, and 6).

[3] N = north; W = west; WSW = west-southwest; WNW = west-northwest.

($P \leq 0.0001$), but not at 0.3 m or as measured with dosi-tubes (Table 2). Similarly, fan number affected ($P \leq 0.0001$) NH_3 concentrations at 1.5 and 3 m with the photoacoustic instrument. Distance downwind from the fans was the factor that showed the most significant effect ($P \leq 0.0001$) on NH_3 concentration at all elevations with both the photoacoustic detector and dositubes. The NH_3 concentration declined sharply from 71.1 ppm near the surface of the fan to 2.1 ppm at 5.5 m downwind from the fans. A further decline in NH_3 concentration to 0.3 ppm at 10 m or 0.1 ppm at 50 m away from the fan was measured; however, these measurements did not differ statistically from the 5.5-m measurement. This pattern was also observed with the dosi-tube measurements. Ammonia concentration measured at 0.3- and 3-m elevations showed a higher concentration at a 5.5-m distance from the fans as compared with 10 m away ($P \leq 0.0001$; e.g., 1.3 vs. 0.3 ppm and 1.0 vs. 0.4 ppm, respectively). Trees downwind from the fans reduced NH_3 concentrations significantly at elevations of both 0.3 and 3.0 m; however, no statistical differences were detected at the 1.5-m elevation. This was followed by a significant interaction of distance by condition at 3 m ($P \leq 0.05$), again suggesting that when the trees were present, aerial NH_3 levels were reduced.

Plant foliar N concentrations were significantly affected by measurement day ($P \leq 0.0001$) and fan combination, as shown in Table 3. The effect of the distance on plant foliar N was linear ($P \leq 0.0001$), with concentrations decreasing with greater distance downwind from the fans: 3.55% at 3.5 m, 2.71% at 6.5 m, 2.43% at 9.5 m, and 2.32% at 50 m. Plant foliar DM concentration was also influenced by day and distance ($P \leq 0.0001$), although the reductions were only discernable at the 50-m distance from the fans. Condition (trees vs. no trees) clearly influenced the concentrations of N ($P \leq 0.0001$) and DM ($P \leq 0.05$) in the plant foliage. Both parameters were higher when the foliage was sampled from the plants downwind from the fans compared with those plants away from the fans (2.89 vs. 2.63% and 36.81 vs. 33.72%, respectively). The effect of distance and condition became clearer in the interaction of these 2 factors, which was also evident on foliar N ($P \leq 0.005$) and DM ($P \leq 0.05$). Plant species affected ($P \leq 0.0001$) foliar N and DM, but only foliar N was affected by the interaction of distance and species ($P \leq 0.0001$). Foliar N was greater ($P \leq 0.05$) in willow (3.52%) and lilac (3.33%) when compared with hackberry (2.68%), fir (2.13%), or juniper (2.09%; Table 3). However, this trend did not hold for foliar DM, for which lilac and hackberry showed the lowest and greatest percentages, respectively, with the other species in between. No interaction of condition × species or distance × condition × species was observed on these parameters.

Measurement day and distance from the fans significantly influenced aerial dust weight (Table 4). Although the differences were not clear at distances of 2.5 and 4.5 m (455.8 vs. 280.0 mg/h), they were significantly reduced with distances of 6.5 and 50 m (148.5 and 2.4 mg/h), respectively. Condition (trees vs. no trees) had no effect on aerial dust weight (245.3 vs. 198.0 mg/h), nor was there an interaction effect of distance × condition. The reduced amounts of aerial dust at greater distances from the fans (Table 4) were also depicted by reduced amounts of $PM_{2.5}$ ($P \leq 0.005$), PM_{10} ($P \leq 0.0001$), $PM_{>10}$ ($P = 0.0661$), and total PM ($P \leq 0.0001$) on foliage samples (Table 5). Plant species also had unique and significant effects on the ability to capture different PM sizes. Foliar $PM_{2.5}$ ($P \leq 0.05$) was better captured by willow compared with juniper (0.0193 vs. 0.0033 mg/cm^2), and this was supported by the interaction effect ($P \leq 0.05$) of distance × species. However, juniper was superior to willow in trapping PM_{10} (0.0374 vs. 0.0219 mg/cm^2).

DISCUSSION

Lower wind speed when the trees were in place relative to that when the trees were absent indicated a barrier effect of vegetation to airborne farm emissions. This finding was also reported by other authors [14, 22] and confirmed our previous findings [17]. However, different ventilation equipment or fan hoods might result in different findings.

Measuring NH_3 at the fan level (1.5 m) and a 0-m distance resulted in the greatest concentration (>70 ppm). From 5.5 m downwind from the fans, NH_3 concentration was significantly lower (±2 ppm) and remained unchanged up to 50 m

Table 2. Ammonia concentrations measured downwind of the four 61-cm exhaust fans[1] of the henhouse under 2 conditions (trees vs. no trees) at distances of 0, 5.5, 10, and 50 m and at 3 different elevations (0.3, 1.5, and 3.0 m) at each distance

	Photoacoustic			
Factor	0.3 m	1.5 m	3.0 m	Tubes
	(ppm)			(ppm/h)
Day[2] (pooled from 2 conditions)				
1st	0.7	17.1^{b}	0.4^{b}	19.7
2nd	0.9	18.3^{ab}	0.6^{b}	20.7
3rd	0.9	19.9^{a}	1.1^{a}	18.9
Fan				
1	1.0	25.5^{a}	0.9^{a}	20.3
2	0.8	14.6^{b}	1.1^{a}	19.0
3	0.6	16.8^{b}	0.4^{b}	21.4
4	0.8	16.7^{b}	0.3^{b}	18.4
Distance (downwind of the fan)				
0 m	—[3]	71.1^{a}	—[3]	74.9^{a}
5.5 m	1.3^{a}	2.1^{b}	1.0^{a}	3.5^{b}
10 m	0.3^{b}	0.3^{b}	0.4^{b}	0.8^{b}
50 m	—[3]	0.1^{b}	—[3]	0.0^{b}
Condition (pooled from 3 d)				
Trees	0.6^{b}	18.8	0.3^{b}	20.2
No trees	1.0^{a}	18.0	1.1^{a}	19.4
Distance × condition				
0 m × trees	—	73.4	—	
0 m × no trees	—	68.8	—	77.6
5.5 m × trees	1.0	1.7	0.4^{bc}	72.1
5.5 m × no trees	1.6	2.4	1.5^{a}	4.2
10 m × trees	0.1	0.1	0.1^{c}	0.4
10 m × no trees	0.5	0.5	0.7^{b}	1.1
50 m × trees	—	0.1	—	0.0
50 m × no trees	—	0.1	—	0.0
SEM[4]	0.4	1.3	0.4	3.3
Source of variance	Probability			
Day	0.2220	0.0362	0.0001	0.7905
Fan	0.0948	0.0001	0.0001	0.7608
Distance	0.0001	0.0001	0.0001	0.0001
Condition	0.0001	0.3258	0.0001	0.6992
Distance × condition	0.2082	0.1106	0.0117	0.6626

[a–c] Means in a column with no common superscripts differ significantly ($P \leq 0.05$).

[1] Additional anhydrous NH_3 was released from an NH_3 tank (set at 1.79 kg/cm) into 4 fans through 2 flow meters at the rate of 1.5 L/min. Each flow meter released the NH_3 into 2 fans for 8 h.

[2] Measurement days (the first, second, and third days of NH_3 measurements were performed on d 1, 2, and 3 when the trees were in place, whereas the corresponding NH_3 measurements when the trees were removed from the pots were performed on d 4, 5, and 6).

[3] Ammonia concentrations were not recorded at the 0.3- and 3.0-m elevations at the 0- and 50-m distances.

[4] Standard errors of the means, mean of 7 readings with the photoacoustic detector or one 8-h reading with the dosi-tubes.

away. Most of the NH_3 emitted from livestock farms is deposited onto the land adjacent to the source (farm), even though it can travel greater distances, especially in the particulate phase [2, 34, 35]. Pitcairn et al. [36] found less than half the NH_3 concentration at 50 m away from the fans relative to concentrations close to the fans. This finding suggests that microclimate and vegetation played a significant role in reducing NH_3 levels, by NH_3 either escaping into the atmo-

Table 3. Foliar N and DM concentration of plants sampled downwind from the 2 pairs of 61-cm henhouse exhaust fans[1]

Factor	N (%, DM basis)	DM (%)
Day[2] (pooled from 2 conditions)		
1st	3.01^{a}	39.70^{a}
2nd	2.71^{b}	31.96^{b}
3rd	2.53^{c}	34.13^{b}
Fan[3]		
1 and 2	2.84^{a}	34.73
3 and 4	2.66^{b}	35.80
Distance (downwind of the fan)		
3.5 m	3.55^{a}	37.65^{a}
6.5 m	2.71^{b}	37.49^{a}
9.5 m	2.43^{c}	38.08^{a}
50 m	2.32^{c}	27.86^{b}
Condition (pooled from 3 d)		
Trees	2.89^{a}	36.81^{a}
No trees	2.63^{b}	33.72^{b}
Species		
Fir	2.13^{c}	32.99^{b}
Hackberry	2.68^{b}	41.41^{a}
Juniper	2.09^{c}	36.70^{ab}
Lilac	3.33^{a}	26.38^{c}
Willow	3.52^{a}	38.84^{ab}
Distance × condition		
3.5 m × trees	3.86^{a}	38.56^{a}
3.5 m × no trees	3.24^{b}	36.74^{a}
6.5 m × trees	2.75^{c}	37.57^{a}
6.5 m × no trees	2.66^{cd}	37.42^{a}
9.5 m × trees	2.45^{cde}	37.91^{a}
9.5 m × no trees	2.41^{de}	38.21^{a}
50 m × trees	2.45^{cde}	33.21^{a}
50 m × no trees	2.19^{e}	22.50^{b}
Distance × species		
3.5 m × fir	2.64^{c}	36.49
3.5 m × hackberry	3.34^{b}	46.06
3.5 m × juniper	2.50^{c}	37.71
3.5 m × lilac	4.58^{a}	29.26
3.5 m × willow	4.71^{a}	38.73
6.5 m × fir	2.08^{d}	35.65
6.5 m × hackberry	2.49^{c}	43.02
6.5 m × juniper	2.13^{cd}	40.05
6.5 m × lilac	3.30^{b}	27.51
6.5 m × willow	3.53^{b}	41.25
9.5 m × fir	1.83^{d}	35.81
9.5 m × hackberry	2.42^{c}	43.72
9.5 m × juniper	1.78^{d}	41.76
9.5 m × lilac	2.92^{c}	27.79
9.5 m × willow	3.19^{b}	41.19
50 m × fir	1.98^{d}	23.99
50 m × hackberry	2.48^{c}	32.85
50 m × juniper	1.97^{d}	27.26
50 m × lilac	2.52^{c}	20.96
50 m × willow	2.66^{c}	34.21
SEM[4]	0.13	1.87
Source of variance	Probability	
Day	0.0001	0.0001
Fan	0.0014	0.4527
Distance	0.0001	0.0001
Condition	0.0001	0.0362
Species	0.0001	0.0001
Distance × condition	0.0049	0.0144
Distance × species	0.0001	0.9772
Condition × species	0.2230	0.9339
Distance × condition × species	0.7436	0.9997

[a–d] Means in a column with no common superscripts differ significantly ($P \leq 0.05$).

[1] Additional anhydrous NH$_3$ was released from an NH$_3$ tank (set at 1.79 kg/cm) into 4 fans through 2 flow meters at the rate of 1.5 L/min. Each flow meter released the NH$_3$ into 2 fans for 8 h.

[2] Measurement days (the first, second, and third days of NH$_3$ measurements were performed on d 1, 2, and 3 when the trees were in place, whereas the corresponding NH$_3$ measurements when the trees were removed from the pots were performed on d 4, 5, and 6).

[3] Each of the 5 tree species were planted randomly downwind of the 2 pairs of fans (fans 1 and 2; fans 3 and 4).

[4] Standard error of the means, mean of 3 day-replicates (SEM value applies for all the means except the day).

sphere or being taken up by nitrophilus species. The greatest loss probably occurred between 5.5 to 10 m downwind from the fans, as indicated by the significant reduction in NH$_3$ concentration measured by the photoacoustic detector at elevations of 0.3 and 3 m. Ammonia concentrations at 0.3 and 3 m in the presence of trees were less than those with no trees present, implying greater uptake or trapping by the trees.

The positive correlation between aerial NH$_3$ concentration and foliar N status of the plants found in this study has been reported on poultry farms [36, 37] and near cattle feedlots [38]. Therefore, greater foliar N and DM of the plants sampled downwind from the fans, compared with those sampled at distances far away from the fans, highlights the capability of vegetation to hold and utilize NH$_3$-N. Pitcairn et al. [37] was even able to detect declining foliar N among plants at 650 m downwind from the fans. There was no difference in foliar N of the plants between 9.5 and 50 m downwind from fans in the current study, suggesting an optimal trapping of aerial NH_3-N by plant foliage within this close range. Findings of our study and those of Pitcairn et al. [36, 37] implicate the role of air turbulence in the distance NH_3 can travel.

Broad-leaved species appeared to be superior at assimilating aerial NH_y into their mesophyll cells compared with conifers (needle-type foliage) during the present (August) experimental period, with lilac and willow having greater foliar N than juniper and fir. Although the visual appearance of the plants was not documented in the present study, we did not see any significant leaf injury among plants near the fans under the short period of observation. Foliage injury and discoloration have been observed in previous studies in growth chambers when foliage was exposed to continuous NH_3 (4 to 8 ppm) [39, 40]. Under field conditions, NH_3 concentrations equivalent to 5.5 ppm entering the glutamine synthetase-glutamate synthase pathways did not disturb plant cell photosynthesis and transpiration [15]. Thus, favorable microclimatic conditions, including rain cleansing and wind fluctuation as well as lower and variable NH_3 concentrations, might contribute to a greater plant tolerance to NH_3 under field conditions [39]. In other words, the capacity of plant foliage to assimilate NH_3-N did not exceed the critical level [41] in this study, as was seen in chamber studies [39, 40]. The same findings were realized in our previous field [16] and pot-in-pot studies [17] under similar outdoor conditions as those used here.

The presence of trees did not have a significant impact on aerial dust concentrations (455.8 mg/h with trees vs. 198.0 mg/h without trees). However, the values suggested otherwise and the distance × condition interaction showed higher dust measures among the vegetation at 2.5 and 4.5 m (530.6 vs. 381.1 mg/h and 319.0 vs. 241.1 mg/h), respectively, compared with no vegetation. At greater distances of 6.5 and 50 m, lower levels of dust were seen among the trees. Further work will be required to validate the impact of vegetation on PM and dust concentrations and whether they are trapped or dropped by the vegetation and lower air speeds among the trees. Leuty [22] inferred that conifers would be more effective at intercepting livestock par-

Table 4. Aerial dust measured downwind of the four 61-cm exhaust fans of the henhouse under 2 conditions (trees vs. no trees) at distances of 2.5, 4.5, 6.5, and 50 m[1]

Factor	Total weight
	(mg/h)
Day[2] (pooled from 2 conditions)	
1	134.8^{b}
2	153.3^{b}
3	377.0^{a}
Fan	
1	293.5
2	202.6
3	200.4
4	190.2
Distance (downwind of the fan)	
2.5 m	455.8^{a}
4.5 m	280.0^{ab}
6.5 m	148.5^{bc}
50 m	2.4^{c}
Condition (pooled from 3 d)	
Trees	245.3
No trees	198.0
Distance × condition	
2.5 m × trees	530.6
2.5 m × no trees	381.1
4.5 m × trees	319.0
4.5 m × no trees	241.1
6.5 m × trees	130.1
6.5 m × no trees	166.8
50 m × trees	1.7
50 m × no trees	3.1
SEM[3]	0.3
Source of variance	Probability
Day	0.0003
Fan	0.6537
Distance	0.0001
Condition	0.3707
Distance × condition	0.6416

[a–c] Means in a column with no common superscripts differ significantly ($P \leq 0.05$).

[1] Additional anhydrous NH_3 was released from an NH_3 tank (set at 1.79 kg/cm) into 4 fans through 2 flow meters at the rate of 1.5 L/min. Each flow meter released the NH_3 into 2 fans for 8 h.

[2] Measurement days (the first, second, and third days of NH_3 measurements were performed on d 1, 2, and 3 when the trees were in place, whereas the corresponding NH_3 measurements when the trees were removed from the pots were performed on d 4, 5, and 6).

[3] Standard error of the means, mean of 3 day-replicates (applies for all the mean factors except the day).

Table 5. Total particulate matter (PM) weight captured by the foliage of the plants downwind from the exhaust fans of the henhouse at several distances (3.5, 6.5, 9.5, and 50 m)

Factor	$PM_{2.5}$	PM_{10}	$PM_{>10}$	Total PM[1]
	(mg/cm^2)			
Distance (downwind of the fan)				
3.5 m	0.0244^{a}	0.0695^{a}	0.0050	0.0990^{a}
6.5 m	0.0098^{ab}	0.0224^{b}	0.0019	0.0340^{b}
9.5 m	0.0097^{ab}	0.0235^{b}	0.0004	0.0336^{b}
50 m	0.0013^{b}	0.0033^{c}	0.0003	0.0049^{c}
Species				
Juniper	0.0033^{b}	0.0374^{a}	0.0027	0.0434
Willow	0.0193^{a}	0.0219^{b}	0.0011	0.0424
Distance × species				
3.5 m × juniper	0.0053^{b}	0.0815	0.0068	0.0937
3.5 m × willow	0.0435^{a}	0.0575	0.0033	0.1043
6.5 m × juniper	0.0029^{b}	0.0308	0.0031	0.0368
6.5 m × willow	0.0167^{ab}	0.0139	0.0007	0.0312
9.5 m × juniper	0.0030^{b}	0.0308	0.0005	0.0343
9.5 m × willow	0.0164^{ab}	0.0161	0.0003	0.0328
50 m × juniper	0.0018^{b}	0.0064	0.0004	0.0086
50 m × willow	0.0001^{b}	0.0002	0.0002	0.0011
SEM[2]	0.0065	0.0063	0.0019	0.0094
Source of variance	Probability			
Distance	0.0033	0.0001	0.0661	0.0001
Species	0.0172	0.0033	0.2430	0.8830
Distance × species	0.0483	0.5541	0.7415	0.7604

[a–c] Means in a column with no common superscripts differ significantly ($P \leq 0.05$).

[1] The values may be slightly different from the sum of $PM_{2.5}$, PM_{10}, and $PM_{>10}$ in each row because of the rounding of each value to the closest decimal.

[2] Standard errors of the means (n = 3).

ticles and odors than deciduous vegetation. This presumption might hold true when plant architecture is closed rather than open and foliage density is high, such as for conifers relative to broad-leaved plants. This was demonstrated herein by the juniper (conifer) over the willow (deciduous) for PM_{10}. For fine particles ($PM_{2.5}$), juniper showed less capacity at entrapment than willow. Whether the NH_3 and ammonium aerosol component of 2.5-µm PM would be more readily absorbed by willow foliage than juniper needles remains to be determined. Studies by Leuty [22] and Lin et al. [42] recognized that the effect of vegetative buffers on farm odor dispersion was more pronounced when the vegetation was dense or consisted of trees with low optical porosity, such as conifers. Therefore, it is likely that the rate capacity of plant foliage to trap and utilize NH_3-N could be explained in part by the capacity of plants to hold particulates, as seen in the present study with the species effect on foliar N and DM. Our previous field studies showed similar species effects for foliar N, DM [16, 43], and PM [43].

Overall, the present study demonstrates the capacity of plant foliage to trap farm emissions, particularly NH_3 and dust. The effect of plant distance and species on all parameters measured enforces the importance of tree selection and planting arrangement (number of rows, planting density, plant height, and leaf density) on the capacity to improve air quality. The climate around the farm cannot be controlled, but the planting arrangement should take into consideration factors such as prevailing winds, topography, fan placement, and neighbors. In addition to downwind planting for air quality purposes, upwind planting of trees may be used to improve energy efficiency, improve neighbor relations, and beautify poultry and livestock farms.

CONCLUSIONS AND APPLICATIONS

1. During the experimental period (August), trees planted downwind from poultry exhaust fans had the ability to reduce aerial concentrations of NH_3.
2. Plants may benefit from short-term NH_3 exposure, as shown by their greater foliar N downwind from the fans. Foliar N concentration is influenced by exposure time and distance from the NH_3 source.
3. Plant foliar N and DM responses to NH_3 exposure were species-dependent, with greater N retention in streamco willow and lilac than in juniper.
4. Plant foliage also showed the capacity to capture all size categories of dust ($PM_{2.5}$, PM_{10}, $PM_{>10}$, and total PM) from 3.5 to 50 m away from the fans. Juniper appeared to be the most effective PM_{10} trap, whereas streamco willow had a 6-fold greater affinity for holding $PM_{2.5}$ compared with juniper.

REFERENCES AND NOTES

1. Fangmeier, A., A. Hadwiger-Fangmeier, L. Van der Eerden, and H.-J. Jäger. 1994. Effects of atmospheric ammonia on vegetation—A review. Environ. Pollut. 86:43–82.

2. Van der Eeerden, L. J. M., P. H. B. de Viser, and C. J. van Dijk. 1998. Risk of damage to crops in the direct neighborhood of ammonia sources. Environ. Pollut. 102:49–53.

3. Sutton, M. A., and D. Fowler. 2002. Introduction: Fluxes and impacts of atmospheric ammonia on national, landscape, and farm scales. Environ. Pollut. 119:7–8.

4. NRC. 2003. Air Emissions. Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs. Natl. Acad. Press, Washington, DC.

5. United State Environmental Protection Agency. 2005. National Emission Inventory—Ammonia Emission from Animal Agricultural Operations: Revised Draft Report, April 2005. http://www.epa.gov/ttn/chief/net/2002inventory.html Accessed Oct. 2006.

6. Elwinger, K., and L. Svenson. 1996. Effect of dietary protein content, litter, and drinker type on ammonia emission from broiler houses. J. Agric. Res. 64:197–208.

7. Ferguson, N. S., R. S. Gates, J. L. Taraba, A. H. Cantor, A. J. Pescatore, M. L. Straw, M. J. Ford, and D. J. Burnham. 1998. The effect of dietary protein and phosphorus on ammonia concentration and litter composition in broilers. Poult. Sci. 77:1085–1093.

8. Jones, T. A., C. A. Donnelly, and M. S. Dawkins. 2005. Environmental and management factors affecting the welfare of chickens on commercial farms in the United Kingdom and Denmark stocked at five densities. Poult. Sci. 84:1155–1165.

9. Kim, W. K., and P. H. Patterson. 2005. Effects of dietary zinc supplementation on the hen performance, ammonia volatilization, and nitrogen retention in manure. J. Environ. Sci. Health B 40:675–686.

10. Moritz, J. S., A. S. Parsons, N. P. Buchanan, and J. L. Pimentel. 2005. Effect of egg yolk antibodies on broiler performance. Poult. Sci. 85(Suppl. 1):178. (Abstr.)

11. Parker, J., E. O. Oviedo-Rondón, S. Clemente-Hernández, and B. Clack. 2005. Feed additives, and *Eimeria* spp. vaccination and/or infection over microbial uricase activity to reduce ammonia volatilization from broiler manure. Poult. Sci. 85(Suppl. 1):204. (Abstr.)

12. Patterson, P. H., and Adrizal. 2005. Management strategies to reduce air emissions: Emphasis—Dust and ammonia. J. Appl. Poult. Res. 14:638–650.

13. Tyndall, J., and J. Collettii. 2000. Air Quality and Shelterbelts: Odor Mitigation and Livestock Production: A Literature Review. Final Project Report. Forestry Dept., Iowa State Univ., Ames.

14. Malone, G., G. Van Wicklen, S. Collier, and D. Hansen. 2006. Efficacy of vegetative environmental buffers to capture emissions from tunnel ventilated poultry houses. Pages 875–878 in Proc. Workshop on Agric. Air Qual.: State of the Science. Potomac, MD. Dept. Commun. Serv., North Carolina State Univ., Raleigh.

15. Yin, Z.-H., W. Kaiser, U. Heber, and J. A. Raven. 1998. Effects of gaseous ammonia on intracellular pH values in leaves of C_3- and C_4-plants. Atmos. Environ. 32:539–544.

16. Patterson, P. H., Adrizal, R. M. Hulet, R. M. Bates, C. Myers, G. Martin, R. Shockey, and M. van der Grinten. 2008. Vegetative buffers for fan emissions from poultry farms: 1. Temperature and foliar nitrogen. J. Environ. Sci. Health B 43:199–204.

17. Patterson, P. H., Adrizal, R. M. Hulet, R. M. Bates, D. A. Despot, E. F. Wheeler, and P. A. Topper. 2008. The potential for plants to trap emissions from farms with laying hens: 1. Ammonia. J. Appl. Poult. Res. 17:54–63.

18. Reynolds, S. J., D. Y. Chao, P. S. Thorne, P. Subramanian, P. F. Waldron, M. Selim, P. S. Whitten, and W. J. Popendorf. 1998. Field comparison of methods for evaluation of vapor/particle phase distribution of ammonia in livestock buildings. J. Agric. Saf. Health 4:81–93.

19. Siefert, R. L., J. R. Scudlark, A. G. Potter, K. A. Simonsen, and K. B. Savidge. 2004. Characterization of atmospheric ammonia emissions from a commercial chicken house on the Delmarva Peninsula. Environ. Sci. Technol. 38:2769–2778.

20. Borrelli, J., J. Gregory, and W. Abtew. 1989. Wind barriers: A reevaluation of height, spacing, and porosity. Trans. ASAE 32:2023–2027.

21. Raupach, M. R., N. Woods, G. Dorr, J. F. Leys, and H. A. Cleugh. 2001. The entrapment of particles by windbreaks. Atmos. Environ. 35:3373–3383.

22. Leuty, T. 2004. Using shelterbelts to reduce odors associated with livestock production barns. Ministry of Agriculture, Food, and Rural Affairs. Ontario, CA. http://www.omafra.gov.on.ca/english/crops/facts/info_odours.htm Accessed Oct. 2006.

23. The air speed was measured with a no. 451112 thermo-anemometer, Extech Instruments, Waltham, MA.

24. Cole-Parmer Instrument Co., Vernon Hills, IL.

25. Frey Bros., Reading, PA.

26. No. 90326, Scotts-Sierra Horticultural Products Co., Marysville, OH.

27. Model 1412, Innova AirTech Instruments, Ballerup, Denmark. An internally Teflon-coated 31-cm tubing equipped with a 47-mm polycarbonate cassette (no. 1119, Pall Gelman Laboratory, Ann Arbor, MI) and a 20- to 25-μm filter paper (no. 41, Whatman International Ltd., Maidstone, UK) on its air inlet end from each location was connected to a manifold and a vacuum pump (VFA-24-BV, Dwyer Instruments Inc., Michigan City, IN). The pump ran at the rate of 10 L/min. All the air sample lines were continuously purged throughout the pump outlet ports, venting via 0.31-cm tubing to a location 18 m away from the fans, except when a line was connected to the NH_3 detector unit for NH_3 reading.

28. No. 3D, Gastec Corp., Fukaya, Japan.

29. Hobo Pro Series (H08-032-08), Onset Computer, Bourne, MA.

30. Model RJ 1412 HPL Type 4X, Robroy Industries, Belding, MI.

31. Model AFC-123, BGI Incorporated, Waltham, MA. A 37-mm clear styrene cassette (A-003750-3) equipped with a 37-mm (diameter) by 0.8-μm (pore size) mixed cellulose ester filter with support pad (M-083700P; SKC Omega Specialty Division, Houston, TX) was connected via 0.64-cm polyvinyl chloride tubing to the pump. The cassette was loosened from its 3 parts with a cassette opener, and along with the filter and the support pad, they were placed in a desiccator for 30 min. Next, the support pad was fitted onto the bottom part (indicated by a blue plug on the bottom hole) of the cassette. The filter was passed over a static master (to reduce static charge) with a self-closing forceps before being weighed on a micro balance. This was done 3 times to get an average final weight. The filter was then placed on the support pad and covered with the middle part and the top part of the cassette. A red plug was used to cap the nose hole of the cassette. Room temperature and RH were recorded during the weighing time before and after dust measurement. On the site of dust measurement, the blue cap was unplugged from the cassette, connected to the air pump via 0.64-cm tubing, and taped to avoid air leakage. The red cap was unplugged and the cassette was connected to a flow meter to set the pump rate at 2.2 L/min. After disconnecting the flow meter from the nose hole of the cassette, the pump and the cassette were hung on a sheltered metal post at a height of 1.5 m to run for 8 h. Ten minutes after running the pump, poultry dust (scraped from the layer house floor) was flung and released from each fan inlet to increase the dust concentration discharge. Poultry dust was released hourly (1 kg/h per fan for 8 h). Before turning off the pump, the nose hole of the cassette was connected with a flow meter to ensure that the pump was running at approximately the same rate as when it was started. The cassette was then capped on the top, disconnected from the pump, capped on the bottom, and placed in a desiccator before being weighed. The weighing protocol was the same as that described previously when weighing the filter. The difference in weight of the filter before and after measurement and divided by the hours of measurement (8) was the weight of the total dust per hour.

32. Foliage samples were placed in flasks, filtered (0.45-μm pore diameter) water was used to rinse the collection bottles, and the rinse water was added to the corresponding flask. A 0.02% hepamethyltrisiloxane surfactant solution was created by adding 0.095 mL of the surfactant to each flask and bringing the flask to 500 mL with filtered water. The stoppered flasks were placed in a refrigerator and the samples were allowed to soak for 24 h. The flasks were then placed on a rotational shaker at 200 rpm for 2 h. Each sample was then removed from the flask and rinsed over a funnel with filtered water. The samples were sprayed vigorously on all sides, allowing the water to collect in the flasks. The resulting solutions were then successively filtered through 3 preweighed, size-selective filters with 1,000-, 25-, and 0.45-μm pore sizes. The filters were dried for 1 h at 105°C, cooled for 15 min, and then reweighed on a digital microbalance. Leaf area was determined for each vegetative sample. For cylindrical samples, the plant parts were scanned to create digital images. These images were analyzed by using Rootedge software to obtain an area measurement for each sample. For noncylindrical samples, a LiCor (LI-3100C) meter was used to obtain leaf area measurements. Results are reported as the weight of PM captured on each filter per surface area of the vegetative sample (mg/cm^2). Particulate matter filtered from 0.45-μm pore filters was designated as $PM_{2.5}$, the PM with aerodynamic equivalent diameters of less than or equal to 2.5 μm. Particulate matter filtered from 25-μm pore filters was designated as PM_{10}, with aerodynamic equivalent diameters of less than or equal to 10 μm. Particulate matter filtered from 1,000-μm pore filters was designated as $PM_{>10}$, again with PM aerodynamic equivalent diameters of greater than 10 μm. Total PM was counted as the sum of the 3 PM categories.

33. SAS Institute. 2003. SAS for Windows, Version 9.1 ed. SAS Institute Inc., Cary, NC.

34. Webb, J., B. Pain, and M. Sutton. 2002. Background to the problem of ammonia in the UK. Pages 6–13 in Ammonia in the UK. DEFRA, London, UK.

35. McGinn, S. M., H. H. Janzen, and T. Coates. 2003. Atmospheric pollutants and trace gases. J. Environ. Qual. 32:1173–1182.

36. Pitcairn, C. E. R., I. D. Leith, L. J. Sheppard, M. A. Sutton, D. Fowler, R. C. Munro, S. Tang, and D. Wilson. 1998. The relationship between nitrogen deposition, species composition, and foliar nitrogen concentrations in woodland flora in the vicinity of livestock farms. Environ. Pollut. 102(Suppl. 1):41–48.

37. Pitcairn, C. E. R., U. M. Skiba, M. A. Sutton, D. Fowler, R. Munro, and V. Kennedy. 2002. Defining the special impacts of poultry farm ammonia emissions on species composition of adjacent woodland groundflora using Ellenberg Nitrogen Index, nitrous oxide, and nitric oxide emissions and foliar nitrogen as marker variable. Environ. Pollut. 119:9–21.

38. Hao, X., C. Chang, H. H. Janzen, G. Clayton, and B. R. Hill. 2006. Sorption of atmospheric ammonia by soil and perennial grass downwind from two large cattle feedlots. J. Environ. Qual. 35:1960–1965.

39. Adrizal, P. H. Patterson, R. M. Hulet, and R. M. Bates. 2006. Growth and foliar nitrogen status of four plant species exposed to atmospheric ammonia. J. Environ. Sci. Health B 41:1001–1018.

40. Adrizal, P. H. Patterson, R. M. Hulet, and R. M. Bates. 2006. Foliar nitrogen status and growth of plants exposed to atmospheric ammonia (NH_3). Pages 442–452 in Proc. Workshop on Agric. Air Qual.: State of the Science. Potomac, MD. Dept. Commun. Serv., North Carolina State Univ., Raleigh.

41. Krupa, S. V. 2003. Effects of atmospheric ammonia (NH_3) on terrestrial vegetation: A review. Environ. Pollut. 124:179–221.

42. Lin, X.-J., S. Barrington, J. Nicell, D. Choinière, and A. Vézina. 2006. Influence of windbreaks on livestock

odour dispersion plume in the field. Agric. Ecosyst. Environ. 116:263–272.

43. Patterson, P. H., Adrizal, R. M. Hulet, R. M. Bates, C. Myers, G. Martin, R. Shockey, M. van der Grinten, and J. R. Thompson. 2008. Vegetative buffers for fan emissions from poultry farms: 2. Ammonia, dust, and foliar nitrogen. J. Environ. Sci. Health B 43:96–103.

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